



UNIVERSITE DE LIEGE

FACULTE DE MEDECINE

DEPARTEMENT DE SCIENCES BIOMEDICALES ET PRECLINIQUES

SERVICE D'ANATOMIE HUMAINE

**OUTILS NUMERIQUES DANS L'ENSEIGNEMENT ET
L'APPRENTISSAGE DE L'ANATOMIE HUMAINE :
CONTRIBUTION A L'ELABORATION, L'IMPLEMENTATION ET
L'EVALUATION**

**DIGITAL TOOLS IN THE TEACHING AND LEARNING OF
HUMAN ANATOMY:
CONTRIBUTION TO THE DEVELOPMENT, IMPLEMENTATION,
AND EVALUATION**

Par : David MUTOMBO MWEMBO

Docteur en Médecine,
Spécialiste en Chirurgie Générale

ANNEE ACADEMIQUE 2025-2026

*Thèse défendue en vue de l'obtention du grade de
doctorat en sciences médicales.*

Liège, le 26 mai 2026



UNIVERSITE DE LIEGE

FACULTE DE MEDECINE

DEPARTEMENT DE SCIENCES BIOMEDICALES ET PRECLINIQUES

SERVICE D'ANATOMIE HUMAINE

**OUTILS NUMERIQUES DANS L'ENSEIGNEMENT ET
L'APPRENTISSAGE DE L'ANATOMIE HUMAINE :**

**CONTRIBUTION A L'ELABORATION, L'IMPLEMENTATION ET
L'EVALUATION**

**DIGITAL TOOLS IN THE TEACHING AND LEARNING OF HUMAN
ANATOMY:**

**CONTRIBUTION TO THE DEVELOPMENT, IMPLEMENTATION, AND
EVALUATION**

Par : David MUTOMBO MWEMBO

THESE PRESENTEE EN VUE DE L'OBTENTION DU GRADE DE

Doctorat en Sciences Médicales

ANNEE ACADEMIQUE 2025-2026

« Là où la nature finit de créer ses espèces, l'homme commence, en utilisant les choses naturelles, à créer à l'infini. »

— *Inspiré de la pensée de Leonardo da Vinci*

MEMBRES DU JURY

Professeur Olivier DETRY (Université de Liège) : Président

Professeur Laurent LEDUC (Université de Liège) : Secrétaire

Professeure Valérie DEFAWEUX (Université de Liège) : Promotrice

Professeur Pierre BONNET (Université de Liège) : Co-promoteur

Professeur Willy ARUNG KALAU (Université de Lubumbashi) : Promoteur de cotutelle

Professeur Jean-Michel VANDEWEERD (Université de Namur) : Membre

Professeur Renaud JEFFREY-GAUTHIER (Université du Québec à Trois-Rivières) : Membre

Professeur Serge VAN SINT JAN (Université Libre de Bruxelles) : Membre

REMERCIEMENTS

L'achèvement de ce travail rappelle qu'une recherche de cette envergure ne saurait être conduite en solitaire. La thèse n'est pas uniquement un exercice scientifique ; elle constitue une démarche profondément humaine, marquée par des collaborations, des soutiens précieux et une présence constante de ceux qui, à différents moments, ont accompagné et encouragé ce parcours. Elle prend ainsi place dans un processus exigeant, nourri par l'engagement intellectuel, la rigueur méthodologique et la persévérance tout au long de l'itinéraire doctoral.

Le présent manuscrit expose des résultats, des analyses et des connaissances, tout en reflétant la contribution de l'ensemble des personnes qui, à divers titres, ont apporté leur soutien à la conduite et à l'aboutissement de ce travail.

Je rends avant tout grâce à Dieu, qui éclaire les intelligences, soutient les volontés et donne sens aux efforts des hommes. Dans les heures de fatigue comme dans celles de lumière, Sa présence a toujours été, et restera mon appui.

Je tiens à exprimer ma profonde reconnaissance à ma promotrice, la **Professeure Valérie DEFAWEUX**, directrice du laboratoire d'anatomie humaine de l'université de Liège, dont la bienveillance attentive, l'exigence intellectuelle et la confiance constante ont jalonné chacune des étapes de ce travail. La hauteur de sa pensée, la justesse de ses conseils et la noblesse de son engagement scientifique ont profondément nourri ma réflexion. À travers son accompagnement, elle m'a offert bien davantage qu'une direction académique : un véritable modèle, un repère.

Je souhaite également rendre un hommage appuyé au **Professeur Pierre BONNET**, co-promoteur de cette thèse, directeur honoraire du laboratoire d'anatomie humaine de l'université de Liège, et artisan de la première heure de cette œuvre. Depuis mes premiers pas dans un univers qui m'était alors encore largement inconnu, il a su m'accueillir, m'orienter avec générosité. Son humanisme profond, allié à l'étendue remarquable de ses connaissances en médecine (et en anatomie humaine tout particulièrement), a constitué un moteur intellectuel et un encouragement constant tout au long de ce parcours.

Que ma gratitude s'adresse au **Professeur Willy ARUNG KALAU**, mon promoteur de cotutelle, mon cher maître, doyen de la faculté de médecine de l'université de Lubumbashi. Par une présence discrète mais toujours juste, il a accompagné mon cheminement avec une attention fidèle et une efficacité remarquable. Son soutien, dès les premiers jalons de mon cursus de chirurgien général, puis dans mon engagement comme chercheur au sein d'un champ encore plus vaste que la chirurgie, a représenté un appui déterminant et structurant pour ma trajectoire académique et professionnelle.

Ce travail n'aurait probablement pas vu le jour sans la vision éclairée du **Professeur Serge VAN SINT JAN**, à l'origine de ce merveilleux projet de réforme de l'enseignement de l'anatomie humaine à l'Université de Lubumbashi, cadre au sein duquel s'inscrit pleinement cette recherche doctorale. Par son engagement, son sens du management et son attachement à l'excellence, il a su insuffler une dynamique qui m'a constamment encouragé à davantage repousser mes limites. Je lui adresse ici l'expression de ma plus sincère gratitude.

Aux **Professeurs Olivier DETRY, Laurent LEDUC et Albert MWEMBO TAMBWE A NKOY**, je tiens à exprimer ma reconnaissance pour l'attention portée à ce parcours et pour la qualité de leur accompagnement. Leurs remarques, leur regard critique et la pertinence de leurs

recommandations ont contribué de manière précieuse à l'affinement de la réflexion scientifique et à la maturation de ce travail.

A **Ninon PUTTAERT** (Maître des conférences et Assistante à la Faculté de Psychologie, Logopédie et Sciences de l'Education de l'Université de Liège) dont l'expertise et la lucidité ont été déterminantes dans la mise au point de ce travail : Au-delà de ses compétences avérées, je salue également sa remarquable disponibilité.

J'exprime aussi toute ma reconnaissance aux institutions académiques dont l'appui a rendu possible la réalisation de ce travail doctoral ; je cite :

- En premier lieu **l'Université de Liège**, qui m'a accueilli et formé dans un cadre scientifique exigeant et stimulant. J'y ai trouvé un environnement intellectuel propice à la réflexion rigoureuse, au dialogue académique et au développement de ce projet de recherche.
- Ensuite **l'Université de Lubumbashi**, mon institution d'origine, pour la confiance accordée et pour le soutien constant apporté tout au long de ce parcours. En m'offrant le cadre institutionnel nécessaire à cette formation doctorale, elle a largement contribué à la réalisation et à l'aboutissement de ce travail.
- Enfin **l'Académie de recherche et d'enseignement supérieur de Belgique** pour l'appui financier déterminant qu'elle m'a accordé.

À travers ces institutions s'est dessiné un cadre académique où la rigueur scientifique, la transmission du savoir et le sens du service de l'homme ont trouvé une convergence féconde.

Ces remerciements s'adressent également à l'ensemble de ceux qui, par leur présence, leur confiance ou leur collaboration, ont contribué à l'aboutissement de ce travail :

- Je tiens à saluer tout particulièrement mes collègues engagés avec moi au sein du **projet en faveur du renforcement de l'enseignement de l'anatomie à l'Université de Lubumbashi** : docteur Athos LUBENGA ALIBABA (ami de longues dates, confrère, compagnon de luttes), Ange EKPOMI KYAKA et Jean-Pierre TSHIBANGU KANYANGA, pour leur collaboration précieuse.
- Je souhaite également adresser toute ma considération à mes collègues du **laboratoire d'anatomie humaine de l'Université de Liège**, qui m'ont accueilli avec une bienveillance remarquable et une générosité sincère. Grâce à eux, je me suis senti pleinement intégré, aimé et porté : Professeur Marc RADERMECKER, Professeure Aude LAGIER, Olivier PRYGIEL, Allyson FRIES, Elodie NEMERY, Louis SCHIERES, Murielle WOUTERS, Alain BOTTE, Caterina MARCHESE, Cécile RODE.
- Je n'aurais pu omettre de mentionner l'ensemble des **membres du département de chirurgie de l'université de Lubumbashi**, mon département d'attache. Leur nombre rend impossible une citation nominative ; mais chacun d'eux a, à sa manière, marqué mon parcours. Leur présence, leur soutien et les échanges partagés au fil des années ont constitué un socle humain et professionnel essentiel . À travers eux s'est transmise cette conviction profonde que la connaissance n'a de valeur que si elle éclaire, élève et sert.

Cette œuvre étant l'aboutissement d'un chemin jamais parcouru seul, il m'est cher d'adresser toute mon affection :

- A mon épouse, **Chrislette OKITO NUMBE**, ainsi qu'à nos enfants, **Noah-Emmanuel MISENGO MUTOMBO** et **Zoé MUTOMBO**. Je souhaite leur adresser des mots simples, parce qu'ils sont les plus vrais : Merci d'avoir accepté mes longues absences, compris

mes silences, supporté mes inquiétudes et partagé mes espérances. Votre affection fidèle a été, dans les jours les plus difficiles, une lumière fine et constante.

- À mes parents, dont l'amour, les sacrifices et les prières ont constitué le premier fondement de mon chemin, je dois plus que je ne saurais l'exprimer.
- À mes frères et sœurs, neveux et nièces, oncles et tantes, cousins et cousines, pour leur inconditionnel soutien et leur présence à chaque étape de ma vie.
- À ma belle-famille, pour son accueil, sa bienveillance et ses encouragements constants.
- À mes amis, pour leurs marques d'attention, leurs mots d'encouragement, leur compréhension et, parfois, leur silence respectueux. Chacun, à sa manière, a contribué à maintenir l'élan et la confiance nécessaires à l'aboutissement de ce travail.

DAIGNEZ ACCEPTER L'EXPRESSION DE MA PROFONDE ET RESPECTUEUSE GRATITUDE !

David MUTOMBO MWEMBO

LISTE D'ABREVIATIONS , ACRONYMES ET SIGLES

- **3D** – Three-Dimensional
- **AR** – Augmented Reality
- **ARanatomy** – Application pédagogique en réalité augmentée
- **ASSURE** – Analyze Learners; State Objectives; Select Media and Materials; Utilize Media and Materials; Require Learner Participation; Evaluate and Revise
- **BCW** – Behavior Change Wheel
- **COVID-19** – Coronavirus Disease 2019
- **e-learning** – Electronic Learning
- **HEPL** – Haute École de la Province de Liège
- **ICNA** – Indice de Compétences Numériques en Anatomie
- **IFAA** – International Federation of Associations of Anatomists
- **LOTI** – Levels of Technology Implementation
- **PIC-RAT** – Passive; Interactive; Creative / Replace; Amplify; Transform
- **PMT** – Protection Motivation Theory
- **RDC** – République Démocratique du Congo
- **SAMR** – Substitution; Augmentation; Modification; Redefinition
- **TPACK** – Technological Pedagogical Content Knowledge
- **ULiège** – Université de Liège
- **UNILU** – Université de Lubumbashi
- **VR** – Virtual Reality
- **WBLT** – Web-Based Learning Tools

TABLES DES MATIERES

REMERCIEMENTS

LISTE D'ABREVIATIONS , ACRONYMES ET SIGLES

RESUME.....1

SECTION I – CADRE CONTEXTUEL ET THÉORIQUE DE L'APPRENTISSAGE DE L'ANATOMIE MEDIÉE PAR LE NUMÉRIQUE.....4

Introduction générale.....5

1 CONTEXTE.....6

2 PROBLEMATIQUE.....7

2.1 Enseignement et apprentissage de l'anatomie dans un contexte à ressources limitées
.....7

2.2 Tendance mondiale à la réduction du volume horaire dans l'enseignement de l'anatomie
.....9

2.3 Émergence des environnements numériques en anatomie.....10

2.4 Le numérique en anatomie : une réponse contextuelle plutôt qu'universelle.....11

2.5 La République Démocratique du Congo : un contexte révélateur des enjeux de l'anatomie
numérique Le numérique en anatomie.....13

3 CADRE THEORIQUE ET MODELES D'INTEGRATION DU NUMERIQUE.....14

3.1 Une approche interactionniste de l'apprentissage.....14

3.2 Learning analytics et compréhension des usages.....14

3.3 Alignement pédagogique et intégration du numérique.....15

3.4 Modèles d'intégration pédagogique du numérique.....15

3.5 Synthèse : vers un modèle interactionniste.....16

4 QUESTION DE RECHERCHE ET HYPOTHESES.....16

5 MODELE CONCEPTUEL.....16

5.1 Une dimension structurelle.....17

5.2 Une dimension individuelle.....17

5.3 Une dimension processuelle.....17

5.4 Articulation des dimensions.....18

SECTION II – ANALYSE MULTINIVEAUX DE L'APPRENTISSAGE EN ANATOMIE NUMÉRIQUE :	
DU CONTEXTE AUX USAGES.....	19
Etude 1 — Analyse des dimensions structurelles des dispositifs numériques en anatomie.....	20
Projet d'article: "How, Who, Where—and When—Shape Anatomy Learning: An Interactionist Multicenter Study Across Europe and Sub-Saharan Africa"	22
Etude 2— Analyse des profits des apprenants et des compétences numérique en anatomie.....	43
Article 1: "Development and validation of the ICNA scale: a discipline-specific measure of digital competence in anatomy education"	45
Etude 3 — Niveau processuel (micro) : usages des environnements numériques et engagement des apprenants.....	80
Article 2: "Instrumenting Augmented Reality in Anatomy and Histology Education: What Student Usage Reveals About Engagement, Motivation and Learning in European and Sub-Saharan African Contexts"	82
Discussion générale.....	94
1 DEPASSER UNE LECTURE TECHNOCENTREE DE L'APPRENTISSAGE EN ANATOMIE HUMAINE.....	95
2 ROLE DU CONTEXTE PEDAGOGIQUE ET INSTITUTIONNEL DANS LA CONFIGURATION DES EFFETS DU NUMERIQUE	96
2.1 Le contexte institutionnel comme déterminant majeur des effets du numérique	97
2.2 Du dispositif numérique isolé à l'écosystème pédagogique en anatomie	98
2.3 Contextes à ressources limitées et limites de la transférabilité pédagogique	99
3 COMPETENCES NUMERIQUES DISCIPLINAIRES AUTODECLAREES ET PROFILS D'APPRENANTS EN ANATOMIE HUMAINE	100
3.1 Le profil de l'apprenant comme déterminant clé des effets du numérique	100
3.2 Aptitudes visuospatiales et apprentissage de l'anatomie médiée par le numérique	101
3.3 Des compétences numériques génériques aux compétences numériques disciplinaires autodéclarées (ICNA)	102
3.4 Compétences numériques, stratégies d'apprentissage et mécanismes d'appropriation	102
3.5 Profils d'apprenants, inégalités et contextes de formation	103

4	REPENSER LA NOTION DE PERFORMANCE EN ANATOMIE MEDIEE PAR LE NUMERIQUE	104
4.1	Absence d'amélioration systématique de la performance académique immédiate	105
4.2	Des effets différenciés selon le type de compétences évaluées	105
4.3	L'alignement entre dispositifs numériques et modalités d'évaluation	106
4.4	Vers une conception élargie et médiée de la performance	106
5	L'USAGE REEL : VARIABLE CLE, MAIS ENCORE PARTIELLEMENT INVISIBLE	107
5.1	Des intentions pédagogiques aux usages effectifs des dispositifs numériques	107
5.2	Hétérogénéité des usages et variabilité des effets d'apprentissage	107
5.3	Dynamiques motivationnelles et structuration des usages	108
5.4	Mesures instrumentées des usages : rendre visible l'invisible ?	108
6	LIMITES ET PERSPECTIVES	109
6.1	Limites de cette recherche	109
6.2	Perspectives	109
7	CONCLUSION : VERS UNE COMPREHENSION INTERACTIONNISTE DES EFFETS DU NUMERIQUE EN ANATOMIE HUMAINE ?	110

BIBLIOGRAPHIE.....	111
---------------------------	------------

ANNEXES.....	119
---------------------	------------

Annexes 1. Article: "Beyond The gift: Donor motivations and family experiences as drivers of body donation programs"	119
--	-----

Annexes 2. Tableau récapitulatif.....	134
---------------------------------------	-----

RESUME-ABSTRACT

Résumé

Cette thèse propose une compréhension interactionniste des effets du numérique dans l'apprentissage de l'anatomie humaine, en dépassant les approches technocentrées qui dominent encore la littérature. À partir d'une analyse intégrative articulée en trois niveaux — structurel, individuel et processuel — elle montre que les dispositifs numériques ne possèdent pas d'efficacité pédagogique intrinsèque et que leurs effets dépendent étroitement des contextes institutionnels, des compétences des apprenants et des usages effectifs.

Au niveau structurel, les résultats issus d'études multicentriques menées en Belgique et en République Démocratique du Congo montrent que des dispositifs pédagogiques identiques — qu'ils soient haptiques ou virtuels, avec des niveaux d'interaction variables (actifs ou passifs) — produisent des effets différenciés selon les institutions. L'organisation des enseignements, les cultures pédagogiques et les contraintes matérielles apparaissent ainsi comme des déterminants majeurs, remettant en question toute logique de transférabilité directe des innovations numériques.

Au niveau individuel, la thèse apporte une contribution originale en développant et validant un instrument spécifique — l'Indice de Compétences Numériques en Anatomie (ICNA). Les analyses montrent que ces compétences numérique disciplinaires, multidimensionnelles, autodéclarées jouent un rôle médiateur essentiel entre les outils numériques et les apprentissages observés.

Au niveau processuel, l'étude des usages réels des étudiants avec un environnement numérique spécifique, une application de réalité augmentée, ARanatomy, révèle une forte hétérogénéité des comportements d'interaction. L'engagement apparaît comme une médiation conditionnelle, dépendante des contextes institutionnels, des compétences numériques et des formes d'appropriation des outils.

L'ensemble de ces résultats conduit à un modèle interactionniste empirique des effets du numérique en anatomie, repositionnant celui-ci non comme une solution universelle, mais comme un levier conditionnel dont l'efficacité dépend de son inscription dans des contextes cohérents et de l'accompagnement des usages.

Mots-clés : Anatomie humaine — Dispositifs numériques — Modèle interactionniste

Abstract

This dissertation proposes an interactionist understanding of the effects of digital technologies on the learning of human anatomy, moving beyond the technocentric approaches that still dominate the literature. Drawing on an integrative analytical framework articulated across three levels—structural, individual, and processual—it demonstrates that digital tools do not possess intrinsic pedagogical effectiveness. Their impact on learning depends instead on the institutional contexts in which they are implemented, the profiles and competencies of the learners who use them, and the actual patterns of engagement observed in practice.

At the structural level, results from multicenter studies conducted in Belgium and the Democratic Republic of the Congo show that identical pedagogical devices—whether haptic or virtual, with varying levels of interaction (active or passive)—produce differentiated effects across institutions. The organization of teaching, pedagogical cultures, and material constraints thus emerge as major determinants, calling into question any assumption of direct transferability of digital innovations.

At the individual level, the dissertation introduces and validates a discipline-specific instrument—the Digital Competence Index in Anatomy—highlighting the central mediating role of digital competencies. Results indicate that, even with equivalent tools, learning outcomes vary significantly according to learners' ability to mobilize digital resources appropriately.

At the processual level, analyses of actual usage reveal substantial heterogeneity in interaction patterns. Engagement appears as a conditional mediator: it supports learning only when aligned with institutional affordances, digital competencies, and meaningful appropriation of tools.

Together, these findings lead to an empirically grounded interactionist model of digital learning in anatomy. The dissertation reframes digital technologies not as universal solutions but as conditional levers whose effectiveness depends on coherent institutional integration, intentional development of digital competencies, and supported learner engagement.

Key words: Human anatomy — Digital tools — Interactionist model

SECTION I – CADRE CONTEXTUEL ET THEORIQUE DE L'APPRENTISSAGE DE L'ANATOMIE MEDIEE PAR LE NUMERIQUE

Introduction générale

1 CONTEXTE

L'anatomie constitue l'un des fondements essentiels de la formation des professionnels de santé, en ce qu'elle permet de comprendre l'organisation du corps humain, d'interpréter les examens complémentaires et de réaliser les gestes cliniques et chirurgicaux en toute sécurité (Fevry et al., 2026).

Plusieurs auteurs considèrent ainsi l'anatomie comme l'une des pierres angulaires du cursus médical et soulignent qu'une connaissance anatomique insuffisante peut compromettre la qualité des soins (Turney, 2007; Sbayeh et al., 2016). Même dans les curricula contemporains bénéficiant d'avancées technologiques, l'anatomie demeure un socle essentiel de la précision diagnostique, de la prise en charge thérapeutique et de la sécurité des soins (Darius et al., 2025).

Au-delà de son rôle descriptif, l'apprentissage de l'anatomie engage des processus cognitifs complexes, reposant sur la construction de représentations mentales tridimensionnelles, la navigation entre différentes échelles d'observation (macroscopique, microscopique, radiologique) et l'intégration de connaissances spatiales et fonctionnelles. Dans cette perspective, les aptitudes visuospatiales jouent un rôle central, leur influence sur les performances académiques ayant été largement documentée (Nokovitch et al., 2025).

Sur le plan pédagogique, l'enseignement de l'anatomie s'inscrit dans des environnements d'apprentissage complexes, mobilisant une diversité de ressources — dissections, modèles physiques, imagerie médicale, outils numériques — qui participent conjointement à la construction des connaissances. Cette complexité peut être appréhendée à travers une approche systémique de l'apprentissage, dans laquelle les connaissances ne résultent pas uniquement de l'exposition à un contenu, mais émergent de l'interaction entre l'apprenant, les outils et le contexte (Engeström, 2001 ; Greeno, 1998).

Dans ce cadre, les technologies numériques occupent une place croissante. Loin de constituer de simples supports, elles participent à la transformation des conditions mêmes de l'apprentissage, en modifiant les modalités d'accès au savoir, les formes de représentation des objets anatomiques et les interactions entre apprenants et contenus. Ces environnements numériques — incluant la réalité virtuelle, la réalité augmentée, les modèles tridimensionnels interactifs et les plateformes d'apprentissage — peuvent être conceptualisés comme des dispositifs de médiation cognitive, au sens où ils reconfigurent les processus d'exploration, de manipulation et de compréhension des structures anatomiques (Wickramasinghe et al., 2022 ; Laurillard, 2012 ; Goodyear & Carvalho, 2014).

Par ailleurs, l'émergence des learning analytics permet désormais d'accéder à des traces fines d'activité des apprenants dans ces environnements, ouvrant la possibilité d'analyser l'apprentissage en train de se faire, au-delà des seules mesures de performance finales. Cette évolution marque un déplacement épistémologique majeur : l'apprentissage n'est plus seulement inféré à partir de résultats, mais observé à travers des comportements et des interactions situées (Siemens, 2013 ; Gašević et al., 2015).

C'est dans cette perspective que ce travail se propose d'analyser l'enseignement et l'apprentissage de l'anatomie humaine à travers le prisme des dispositifs numériques, en considérant conjointement les prérequis cognitifs, les ressources pédagogiques disponibles et les conditions institutionnelles de leur mobilisation.

2 PROBLEMATIQUE

Malgré ces évolutions, l'enseignement de l'anatomie est aujourd'hui soumis à une double tension. D'une part, une réduction progressive du volume horaire dans les curricula, largement documentée à l'échelle internationale, limite le temps consacré aux approches traditionnelles telles que la dissection. D'autre part, les exigences cliniques et technologiques associées à la pratique médicale contemporaine ne cessent de croître, nécessitant une maîtrise toujours plus fine des structures anatomiques.

Cette tension est particulièrement marquée dans les contextes à ressources limitées, où les contraintes structurelles, économiques, culturelles et institutionnelles restreignent fortement l'accès aux ressources pédagogiques traditionnelles.

2.1 Enseignement et apprentissage de l'anatomie dans un contexte à ressources limitées

L'enseignement de l'anatomie humaine varie fortement selon les ressources disponibles : alors qu'en Europe il repose généralement sur des laboratoires bien équipés, des programmes structurés de don du corps et des outils numériques avancés, il demeure, dans de nombreux pays à revenu faible ou intermédiaire, fortement entravé par la pénurie de corps humains, l'insuffisance des infrastructures, le manque d'enseignants spécialisés et des contraintes économiques persistantes (Chang Chan et al., 2025). À ces limitations structurelles s'ajoutent des considérations culturelles et religieuses qui freinent davantage l'acceptation du don du corps et complexifient la mise en œuvre de pratiques pédagogiques fondées sur la dissection anatomique (Jones, 2024 ; Djembi et al., 2026).

2.1.1 Contraintes structurelles et pénurie de ressources anatomiques

La Fédération internationale des associations d'anatomistes (International Federation of Associations of Anatomists, IFAA) a recommandé dès 2012 que l'enseignement et la recherche en anatomie reposent exclusivement sur l'utilisation de corps issus de dons volontaires (IFAA, 2014). Néanmoins, dans un contexte de pénuries, cette norme demeure difficilement applicable dans de nombreuses régions du monde. En effet, les anatomistes continuent fréquemment de recourir à des corps dits « non réclamés », n'ayant pas fait l'objet d'un consentement explicite préalable, soulevant ainsi d'importantes questions éthiques et institutionnelles (Habicht et al., 2018).

Cette réalité est particulièrement illustrée par la situation dans plusieurs états d'Afrique, notamment en Éthiopie, où l'enseignement de l'anatomie demeure exclusivement dépendant de corps non réclamés. Aucune des facultés étudiées ne disposait d'un programme formel de don volontaire, les principaux obstacles identifiés avant la pandémie étant les contraintes économiques et l'absence de cadre légal approprié. La pandémie de COVID-19 a par ailleurs aggravé ces difficultés : les restrictions sanitaires, combinées à l'instabilité liée au conflit civil, ont entraîné une diminution significative de l'accès aux corps, accentuant ainsi la pénurie pour les activités de dissection (Wirtu & Manjatika, 2024).

2.1.2 Facteurs socioculturels influençant le don du corps à la science

Dans son analyse des déterminants culturels et religieux du don du corps, Jones (2024) montre que dans de nombreuses régions du monde, la préservation de l'intégrité du corps après la mort constitue une valeur fondamentale. Cette conception est particulièrement marquée dans les pays musulmans, au sein de certaines communautés hindoues, parmi les populations

zouloues d'Afrique du Sud ainsi que dans les communautés maories, et contribue à une acceptation limitée du don du corps à des fins scientifiques et pédagogiques.

Des réticences comparables sont observées dans le contexte bantou gabonais, où le don du corps à la science demeure largement rejeté, malgré la reconnaissance de l'intérêt pédagogique de la dissection anatomique. Les principaux freins identifiés relèvent de l'obligation culturelle de maintenir l'intégrité corporelle, de l'importance accordée aux rites funéraires et du lien symbolique avec les ancêtres. Ces facteurs culturels et spirituels constituent un obstacle majeur à la mise en œuvre de l'enseignement anatomique traditionnel dans ce contexte (Djembi et al., 2026).

Un article récent issu de nos travaux menés au sein du laboratoire d'anatomie de l'Université de Liège montre par ailleurs que la décision de donner son corps s'inscrit dans une dynamique associant motivations individuelles, reconnaissance institutionnelle et implication de l'entourage familial (Defaweux et al., 2026). Le soutien des proches apparaît comme un facteur central de légitimation de la démarche et de réduction des coûts émotionnels associés, notamment en lien avec le processus de deuil.

L'analyse de ces résultats s'appuie principalement sur deux cadres complémentaires, le Behavior Change Wheel (BCW) et la Protection Motivation Theory (PMT), qui permettent d'identifier des déterminants centraux du passage à l'acte et de dégager des leviers d'action concrets. Ces cadres offrent ainsi des axes opérationnels — en matière de communication, de reconnaissance institutionnelle et d'accompagnement des familles — susceptibles d'être mobilisés et adaptés dans d'autres contextes institutionnels, y compris dans des environnements à ressources limitées tels que celui de la RDC (voir Annexe).

2.1.3 Contraintes économiques et organisationnelles des laboratoires d'anatomie

La mise en place et le fonctionnement d'un laboratoire d'anatomie humaine représentent une charge financière considérable, particulièrement difficilement soutenable dans les pays à ressources limitées. Au-delà des coûts liés à la construction ou à l'aménagement des salles de dissection, le respect des normes de sécurité impose l'installation de systèmes de ventilation performants, tandis que la conservation des corps nécessite des équipements spécialisés onéreux, tels que chambres froides, cuves de fixation et produits chimiques. À ces investissements s'ajoutent l'acquisition de tables de dissection, d'instruments, d'équipements de protection individuelle, ainsi que la gestion des déchets biologiques. Le fonctionnement durable de ces infrastructures requiert en outre un personnel qualifié — anatomistes, techniciens et responsables de biosécurité — dont la formation et la rémunération constituent un coût supplémentaire. Dans de nombreux contextes, ces contraintes sont encore accrues par les frais de transport des corps, les procédures administratives complexes et l'absence de programmes structurés de don du corps, rendant ainsi la création ou le maintien de laboratoires d'anatomie fonctionnels difficile, voire impossible, malgré la reconnaissance de leur importance académique et clinique (Goldman, 2010 ; Gabriel & Chia, 2025 ; McMenamin et al., 2025).

2.2 Tendance mondiale à la réduction du volume horaire dans l'enseignement de l'anatomie

La réduction progressive du volume horaire consacré à l'enseignement de l'anatomie dans les facultés de médecine constitue aujourd'hui une tendance mondiale largement documentée.

Plusieurs analyses montrent que les réformes pédagogiques fondées sur l'apprentissage par problèmes, l'intégration des disciplines et l'essor des ressources numériques ont conduit à diminuer le temps dédié aux dissections et aux enseignements magistraux traditionnels. Cette évolution est notamment décrite par Chang Chan et al. (2022), qui mettent en évidence un recul historique et structurel de la place de l'anatomie dans les curricula contemporains, au profit de l'imagerie médicale et d'autres priorités éducatives.

La pandémie de COVID-19 a par ailleurs accentué ce phénomène, en contraignant les institutions à suspendre ou à réduire drastiquement les activités pratiques, y compris l'accès aux salles de dissection (Quatresooz et al., 2021). Les travaux menés aux États-Unis par Longhurst et al. (2022) montrent que la transition rapide vers l'enseignement en ligne, bien qu'ayant permis d'assurer une continuité pédagogique, s'est accompagnée d'une perte des expériences tactiles et spatiales essentielles à l'apprentissage anatomique. Des tendances similaires ont été observées en Australie et en Nouvelle-Zélande (Pather et al., 2020), où les programmes ont été réorganisés dans l'urgence, entraînant une diminution significative des séances de laboratoire. Dans le même sens, Iwanaga et al. (2021) soulignent que la pandémie a amplifié une trajectoire déjà engagée de réduction du temps pratique, conduisant les enseignants à recourir massivement à des outils tridimensionnels, à la réalité virtuelle et aux plateformes numériques pour compenser le manque d'accès aux spécimens cadavériques.

Cependant, malgré ces évolutions curriculaires et ces contraintes organisationnelles, plusieurs études montrent que les étudiants et les jeunes cliniciens ne soutiennent pas cette réduction du volume horaire. Une enquête menée auprès d'anciens étudiants de médecine à l'Université du Michigan indique que les résidents formés après la diminution de l'enseignement anatomique estiment qu'un apprentissage plus approfondi leur aurait été bénéfique, en particulier pour leur préparation clinique. Ces résultats, rapportés par Bohl et Gest (2011), suggèrent même un intérêt pour l'introduction de formations complémentaires en fin de cursus. De manière convergente, une étude comparative menée auprès de plus de 600 étudiants à Cardiff et à Paris montre que l'anatomie est perçue comme une discipline d'importance clinique majeure, en accord avec la perception des professionnels du domaine (Moxham & Plaisant, 2005).

Ainsi, si la réduction du volume horaire en anatomie s'inscrit dans une dynamique globale de transformation des curricula, elle apparaît en tension avec les besoins perçus par les apprenants et les exigences de la pratique clinique. Cette tension souligne la nécessité de repenser les modalités d'enseignement de l'anatomie, non pas uniquement en termes de volume horaire, mais en termes de qualité, de pertinence pédagogique et d'efficacité des dispositifs mobilisés.

2.3 Emergence des environnements numériques en anatomie

2.3.1 Une évolution des dispositifs : de la numérisation à la datafication de l'apprentissage

L'intégration du numérique dans l'enseignement de l'anatomie s'inscrit dans une évolution progressive marquée par plusieurs transformations majeures. Les premiers dispositifs, fondés sur des supports bidimensionnels numérisés (atlas électroniques, modules d'e-learning), visaient principalement à améliorer l'accès aux connaissances et leur diffusion, sans transformation profonde des pratiques pédagogiques (Nieder & Nagy, 2002 ; Cook et al., 2008).

L'émergence des modèles anatomiques tridimensionnels interactifs a ensuite favorisé le développement du raisonnement spatial, en permettant la manipulation virtuelle des structures (Nicholson et al., 2006 ; Triepels et al., 2020). Les technologies immersives, telles que la réalité virtuelle et la réalité augmentée, ont introduit des environnements expérientiels caractérisés par un haut niveau d'interactivité, permettant une exploration active et contextualisée du corps humain (Radianti et al., 2020 ; Moro et al., 2021).

Enfin, les dispositifs les plus récents s'inscrivent dans une logique de datafication de l'apprentissage, reposant sur la collecte de traces d'activité et le développement des learning analytics, qui permettent d'analyser les processus d'apprentissage en situation et non plus uniquement à travers les performances finales (Siemens, 2013 ; Gašević et al., 2015).

2.3.2 Typologie des environnements numériques en anatomie

Les environnements numériques en anatomie peuvent être organisés selon une typologie à complexité et degrés d'interactivité croissants. Les dispositifs d'e-learning constituent la forme la plus répandue et reposent principalement sur des modalités d'apprentissage autorégulé, centrées sur l'accès aux contenus (Ruiz et al., 2006).

Les modèles anatomiques 3D interactifs offrent une visualisation volumétrique favorisant la compréhension des relations spatiales, avec des effets dépendants de compétences visuospatiales des apprenants (Luursema et al., 2008 ; Yamine & Violato, 2015).

Les technologies de réalité virtuelle et augmentée se distinguent par leur niveau élevé d'immersion et d'interactivité, modifiant les modalités d'exploration et d'engagement des apprenants (Azuma, 1997 ; Moro et al., 2021).

Enfin, les environnements de simulation et les plateformes instrumentées orientées vers l'analyse des traces d'usage constituent des dispositifs émergents à fort potentiel pédagogique, permettant une observation fine des comportements d'apprentissage (Issenberg et al., 2005 ; Winne, 2020).

2.3.3 Transformation des fonctions pédagogiques : de l'accès au savoir à la traçabilité des apprentissages

Parallèlement à l'évolution des dispositifs, les fonctions pédagogiques du numérique ont connu une transformation significative. Initialement limité à une fonction d'accès et de diffusion des connaissances, le numérique s'est progressivement enrichi d'une fonction de visualisation avancée avec les outils tridimensionnels, soutenant la construction de représentations mentales spatiales complexes (Hoffman & Vu, 1997).

La dimension interactive des environnements numériques favorise ensuite l'apprentissage actif et l'engagement cognitif, en permettant à l'apprenant d'interagir directement avec les objets d'apprentissage et de réguler son parcours (Chi & Wylie, 2014).

Les environnements contemporains introduisent désormais une fonction de traçabilité, fondée sur l'analyse des usages et des parcours d'apprentissage, ouvrant des perspectives nouvelles en matière d'évaluation, de rétroaction et de personnalisation des apprentissages (Gašević et al., 2015). Dans le domaine de l'histologie, cette évolution se traduit notamment par l'exploitation de traces fines d'interaction issues de plateformes de microscopie virtuelle, telles que Cytomine. Les travaux récents réalisés au sein de notre équipe de recherche ont ainsi montré que l'analyse de ces traces, combinée à des approches de machine learning, permet d'identifier des profils d'apprentissage et de prédire les performances académiques à partir des comportements d'exploration des étudiants, offrant une compréhension plus fine des processus d'apprentissage en situation (Fries et al., 2023).

Ainsi, le numérique ne se limite plus à un support de transmission, mais constitue un environnement structurant les modalités mêmes de l'apprentissage.

2.3.4 Une tension persistante entre innovation technologique et efficacité pédagogique

Malgré les promesses associées aux environnements numériques, la littérature met en évidence une tension persistante entre innovation technologique et preuves empiriques d'efficacité. Si des effets positifs sont régulièrement observés sur la motivation, l'engagement ou la flexibilité des apprentissages, les gains en termes d'apprentissage demeurent hétérogènes et dépendants des contextes (Cook et al., 2015; Radianti et al., 2020).

Plusieurs travaux rappellent que les technologies n'ont pas d'effet intrinsèque sur l'apprentissage et que leur efficacité dépend des conditions d'intégration pédagogique, des usages effectifs et des caractéristiques des apprenants (Clark, 1983 ; Kozma, 1994).

Dans le champ spécifique de l'anatomie, cette tension est particulièrement marquée : certaines études mettent en évidence des bénéfices associés aux outils numériques, tandis que d'autres ne montrent aucune différence significative par rapport aux méthodes traditionnelles (Yammine & Violato, 2015).

Ces résultats invitent à dépasser une approche technocentrée pour privilégier une analyse des conditions d'efficacité des dispositifs numériques.

2.4 Le numérique en anatomie : une réponse contextuelle plutôt qu'universelle

Malgré les contraintes structurelles, culturelles et économiques qui caractérisent de nombreux environnements à ressources limitées, plusieurs institutions en Afrique, en Asie, en Europe et en Amérique latine parviennent à maintenir un enseignement de l'anatomie fonctionnel grâce à des approches pédagogiques alternatives, telles que l'e-learning, l'apprentissage visuel ou encore l'usage des réseaux sociaux, souvent soutenues par un fort engagement des enseignants. Comme le soulignent Chang Chan et al. (2025), ces adaptations illustrent la nécessité d'aligner les pratiques pédagogiques sur les réalités locales plutôt que de chercher à transposer des standards internationaux parfois difficilement applicables dans ces contextes.

Face à ces contraintes, de nombreuses institutions se tournent vers des solutions pédagogiques plus accessibles, notamment les modèles anatomiques tridimensionnels, les

tables anatomiques virtuelles ou encore la réalité augmentée. Ces outils numériques permettent de compenser, au moins partiellement, l'absence ou l'insuffisance de corps humains destinés à la dissection, tout en offrant aux étudiants un accès répété, standardisé et potentiellement interactif aux structures anatomiques. À cet égard, McMenamin et al. (2025) proposent l'utilisation de répliques anatomiques issues de l'impression 3D à partir de dissections réelles, dont l'efficacité pédagogique, validée dans certains environnements contraints, témoigne de leur potentiel comme alternatives viables, accessibles et éthiquement acceptables.

Dans le même esprit, plusieurs auteurs recommandent de privilégier des approches fondées sur l'imagerie médicale, la dissection virtuelle et la réalité augmentée lorsque l'accès aux corps humains demeure limité. Djembi et al. (2026) soulignent explicitement la pertinence de ces solutions dans le contexte de l'Afrique centrale, où les barrières culturelles et religieuses restreignent le don du corps à la science. De même, Chatha (2024) montre que la réalité virtuelle, la réalité augmentée et les modèles tridimensionnels constituent des alternatives particulièrement adaptées aux environnements à ressources limitées.

Pris ensemble, ces travaux convergent vers l'idée que la résilience de l'enseignement anatomique dans les contextes contraints repose sur une combinaison de stratégies pédagogiques adaptées et de solutions technologiques capables de compenser, au moins en partie, les déficits matériels et infrastructurels persistants.

Toutefois, l'intégration du numérique dans l'enseignement de l'anatomie soulève également plusieurs défis. D'une part, elle se heurte fréquemment à une résistance au changement, particulièrement dans des disciplines historiquement ancrées dans des pratiques traditionnelles telles que la dissection. Cette résistance reflète moins un rejet des technologies qu'une difficulté à articuler les nouveaux outils avec les habitudes pédagogiques existantes, le manque de temps, l'insuffisance de formation ou encore la crainte d'une dégradation de la qualité de l'enseignement. Plusieurs études montrent ainsi que les enseignants tendent davantage à adapter les innovations numériques à leurs pratiques préexistantes qu'à transformer en profondeur leurs approches pédagogiques (Provenzo, 1986 ; Westberry et al., 2015).

D'autre part, l'accès aux outils numériques demeure profondément inégal à l'échelle mondiale, révélant une fracture persistante entre pays à revenu élevé et pays à faibles ressources. Ces inégalités concernent non seulement la connectivité, mais également la qualité des équipements, la fiabilité des infrastructures et les compétences numériques nécessaires à l'appropriation des dispositifs (Lythreath et al., 2022). En 2022, plus de 90 % de la population des pays à revenu élevé utilisait Internet, contre environ 26 % dans les pays à faible revenu (World Bank, 2024). De telles disparités limitent l'intégration effective du numérique dans l'enseignement et constituent un obstacle majeur au déploiement de solutions pédagogiques innovantes en anatomie.

Dans ce contexte, le numérique ne peut être envisagé ni comme une solution universelle, ni comme un levier intrinsèquement efficace. Ses effets apparaissent plutôt dépendants des conditions d'intégration, des caractéristiques des apprenants et des usages pédagogiques qui en sont faits. Les résultats rapportés dans la littérature invitent ainsi à dépasser l'opposition entre enseignement « traditionnel » et numérique pour privilégier une lecture plus intégrative, centrée sur les conditions dans lesquelles les dispositifs technologiques soutiennent — ou non — les apprentissages.

À ce jour, aucune étude comparative multicentrique conduite entre des contextes institutionnels à niveaux de ressources contrastés n'a, à notre connaissance, examiné de manière

systematique les effets du numérique dans l'apprentissage de l'anatomie, conférant à ce travail un caractère pionnier. Cette problématique apparaît particulièrement importante dans plusieurs contextes d'Afrique subsaharienne, où les contraintes structurelles, pédagogiques et technologiques influencent directement les modalités d'appropriation des environnements numériques d'apprentissage.

2.5 La République Démocratique du Congo : un contexte révélateur des enjeux de l'anatomie numérique

La République Démocratique du Congo constitue un exemple particulièrement représentatif des tensions qui traversent actuellement l'enseignement de l'anatomie dans les contextes à ressources limitées. Les difficultés liées au don du corps à la science, l'insuffisance des infrastructures spécialisées, les contraintes économiques ainsi que les disparités d'accès aux ressources pédagogiques rendent particulièrement complexe le maintien d'un enseignement pratique reposant sur les approches anatomiques traditionnelles. Les exigences associées à ces approches — notamment en matière de biosécurité et de personnel qualifié — dépassent souvent les capacités institutionnelles disponibles, limitant ainsi le développement de structures conformes aux standards requis.

Ainsi, le laboratoire d'anatomie de la Faculté de médecine de l'Université de Lubumbashi — l'une des rares structures répondant aux exigences — constitue une initiative notable. Développé dans le cadre d'un partenariat académique avec deux Universités Belges (université Libre de Bruxelles et Université de Liège) et soutenu par l'Académie de Recherche et d'Enseignement Supérieur de Belgique (ARES), ce projet débuté en 2022 a permis d'améliorer considérablement les équipements et de soutenir le développement des compétences pédagogiques, contribuant ainsi à une meilleure préparation des étudiants aux exigences de la pratique médicale et chirurgicale.

Malgré les progrès accomplis, les besoins demeurent considérables au regard des réalités démographiques, sanitaires et académiques de ce pays de plus de cent millions d'habitants. Cette situation souligne la nécessité de concevoir des approches pédagogiques alternatives adaptées aux réalités institutionnelles locales, sans reposer uniquement sur la disponibilité des technologies.

Dans une telle configuration, les enjeux ne concernent pas uniquement la disponibilité des ressources anatomiques, mais également la capacité des institutions à mettre en œuvre des modalités pédagogiques adaptées à leurs contraintes structurelles. Cette problématique est particulièrement marquée à la Faculté de Médecine de l'Université de Lubumbashi, caractérisée par des effectifs étudiants très élevés, avoisinant, pour chaque année académique, 3000 étudiants répartis dans les deux premières années du cursus médical où l'anatomie est enseignée (selon le programme en vigueur). Il s'agit d'une situation liée notamment à l'absence — ou au caractère très limité — de mécanismes sélectifs à l'admission aux études de médecine, et qui exerce une pression considérable sur les infrastructures pédagogiques ainsi que sur l'ensemble des ressources d'encadrement.

Dans ce contexte, les outils numériques apparaissent comme des pistes susceptibles de soutenir l'enseignement de l'anatomie dans des environnements où l'accès aux laboratoires, aux spécimens anatomiques et aux équipements spécialisés demeure limité. Toutefois, leur implémentation reste elle-même conditionnée par de nombreuses contraintes liées aux infrastructures, à la connectivité, aux ressources financières et à la formation techno-pédagogique des enseignants.

C'est dans cette dynamique qu'a été entièrement développée la présente recherche doctorale qui associe réflexion pédagogique, développement d'outils numériques et analyse des conditions d'implémentation.

L'objectif de cette recherche n'est dès lors pas uniquement d'évaluer isolément la performance d'outils numériques, mais de comprendre dans quelles conditions ces dispositifs peuvent effectivement soutenir l'enseignement et l'apprentissage de l'anatomie humaine. Une telle approche implique de dépasser une lecture strictement technocentrée des innovations pédagogiques pour privilégier une compréhension plus intégrative des apprentissages, dans laquelle les effets du numérique émergent de l'interaction entre contextes institutionnels, profils d'apprenants et usages effectifs des technologies.

3 CADRE THEORIQUE ET MODELES D'INTEGRATION DU NUMERIQUE

3.1 Une approche interactionniste de l'apprentissage

Au-delà de ces constats empiriques, la question de l'intégration du numérique dans l'enseignement de l'anatomie ne peut être pleinement comprise sans un ancrage théorique explicite. Une large partie de la littérature a en effet longtemps adopté une approche technocentrique, visant à comparer l'efficacité de différents outils numériques sans interroger les conditions de leur appropriation ni les mécanismes sous-jacents à l'apprentissage.

Or, plusieurs travaux en sciences de l'éducation ont montré les limites de ces approches comparatives, soulignant que les effets des technologies sur l'apprentissage ne peuvent être dissociés des contextes dans lesquels elles sont utilisées ni des caractéristiques des apprenants (Clark, 1983 ; Kozma, 1994 ; Kirschner & De Bruyckere, 2017).

Ce travail va dans le sens d'une approche interactionniste de l'apprentissage, selon laquelle les connaissances émergent de l'interaction dynamique entre trois pôles : les dispositifs pédagogiques, les caractéristiques des apprenants et les usages effectifs des technologies. Cette conception s'inscrit dans le prolongement de la théorie de l'activité (Engeström, 2001), ainsi que des travaux sur les environnements d'apprentissage médiatisés par les technologies (Goodyear & Carvalho, 2014), qui mettent en évidence la nécessité d'articuler dimensions structurelles, individuelles et processuelles de l'apprentissage.

Dans le domaine spécifique de l'anatomie, cette approche apparaît particulièrement pertinente, dans la mesure où les outils numériques ne se limitent pas à transmettre de l'information, mais reconfigurent en profondeur les modalités d'exploration du corps humain, notamment en termes de visualisation tridimensionnelle, de navigation spatiale et d'interactivité.

3.2 Learning analytics et compréhension des usages

Dans le prolongement de cette approche interactionniste, les travaux en learning analytics apportent un éclairage essentiel sur les mécanismes d'apprentissage médiatisés par le numérique. En permettant l'analyse des traces d'activité des apprenants, ces approches offrent un accès direct aux processus d'apprentissage en train de se dérouler, au-delà des seules mesures de performance finales.

Ces recherches montrent que les technologies n'ont pas d'effet intrinsèque sur l'apprentissage ; elles constituent des environnements de possibilités dont les effets dépendent des formes d'engagement et des stratégies d'utilisation des apprenants (Gašević et al., 2015 ; Winne, 2020).

Dans le champ de l'anatomie, l'exploitation de ces traces permet notamment d'identifier des profils d'usage différenciés et de mieux comprendre les liens entre comportements d'exploration, engagement et performance. Les environnements numériques apparaissent ainsi non seulement comme des supports d'apprentissage, mais également comme des systèmes générateurs de données permettant d'analyser finement les dynamiques d'apprentissage.

3.3 Alignement pédagogique et intégration du numérique

L'intégration des technologies numériques dans l'enseignement supérieur, et en particulier dans le domaine de l'anatomie, ne peut être réduite à une simple question d'équipement ou d'innovation technologique. Elle implique une transformation plus profonde des pratiques pédagogiques, nécessitant un alignement cohérent entre les objectifs d'apprentissage, les activités proposées aux apprenants et les modalités d'évaluation.

Cette exigence renvoie au principe de l'alignement constructif aussi appelé triple concordance pédagogique (Biggs, 1996 ; Leclercq, 2006), selon lequel l'efficacité d'un dispositif d'enseignement repose sur la cohérence entre ce que l'on attend des étudiants, ce que l'on leur fait faire et la manière dont leurs acquis sont évalués.

Dans le domaine de l'anatomie, cet alignement est d'autant plus crucial que les compétences visées sont multiples (factuelles, visuospatiales, cliniques) et mobilisent des dispositifs variés. L'intégration du numérique ne peut dès lors être pertinente que si elle s'inscrit dans une logique pédagogique explicite, articulée autour des objectifs d'apprentissage.

3.4 Modèles d'intégration pédagogique du numérique

Plusieurs modèles théoriques ont été développés afin de guider l'intégration du numérique dans les environnements d'apprentissage. Bien que distincts, ces modèles convergent vers une idée centrale : la technologie ne produit d'effets sur l'apprentissage que lorsqu'elle est intégrée de manière intentionnelle, cohérente et contextualisée.

Le modèle SAMR (Puentedura, 2006) propose une classification des usages du numérique en quatre niveaux, allant de la substitution à la redéfinition des tâches. S'il permet de rendre visible le degré de transformation pédagogique, il reste toutefois limité par l'absence d'un ancrage explicite dans les processus d'apprentissage.

Afin de dépasser ces limites, le modèle TPACK (Mishra & Koehler, 2006) propose une approche intégrative fondée sur l'articulation entre trois types de connaissances : disciplinaires, pédagogiques et technologiques. Il met ainsi en évidence que l'efficacité de l'enseignement repose sur la capacité à mobiliser ces dimensions de manière conjointe.

D'autres modèles, tels que ASSURE (Heinich et al., 2001), PIC-RAT (Kimmons et al., 2022) ou encore le Technology Integration Matrix (Florida Center for Instructional Technology, 2005), proposent des cadres d'analyse centrés respectivement sur la conception pédagogique, le rôle de l'apprenant et la qualité des environnements d'apprentissage.

Par ailleurs, les travaux de Roblyer et Doering (2014) et le modèle LOTI (Moersch, 1995, 2002) mettent en évidence le rôle déterminant des facteurs contextuels dans l'adoption des technologies, tandis que le concept de blended learning (Graham, 2006) souligne l'intérêt d'une articulation entre modalités présentiels et numériques.

3.5 Synthèse : vers un modèle interactionniste

Dans leur ensemble, ces approches mettent en évidence la nécessité de dépasser une vision technocentrée de l'apprentissage pour adopter une perspective intégrative, dans laquelle les effets du numérique résultent de l'interaction entre plusieurs dimensions.

Toutefois, pris isolément, ces modèles ne permettent pas de rendre pleinement compte de la complexité des environnements d'apprentissage en anatomie, en particulier dans des contextes institutionnels contrastés.

Dans cette perspective, ce travail propose de mobiliser un modèle interactionniste articulé autour de trois dimensions complémentaires : une dimension structurelle, relative aux dispositifs et aux contextes pédagogiques ; une dimension individuelle, centrée sur les caractéristiques des apprenants ; et une dimension processuelle, portant sur les usages effectifs des technologies.

Ce cadre permet d'analyser de manière intégrée les conditions d'efficacité des environnements numériques d'apprentissage et constitue le fondement du modèle conceptuel développé dans cette thèse.

4 QUESTION DE RECHERCHE ET HYPOTHESES

Au regard des éléments théoriques et empiriques précédemment présentés, cette recherche vise à répondre à la question suivante :

Dans quelle mesure, et selon quelles conditions, les effets des dispositifs numériques sur l'apprentissage de l'anatomie varient-ils en fonction des interactions entre le contexte pédagogique, le profil des apprenants et les usages effectifs des technologies, dans des contextes institutionnels contrastés ?

Sur cette base, nous formulons l'hypothèse générale suivante :

Les effets du numérique sur l'apprentissage de l'anatomie ne sont pas intrinsèques aux outils eux-mêmes, mais résultent de l'interaction dynamique entre :

- le contexte pédagogique (modalités d'enseignement, dispositifs, institutions),
- le profil des apprenants (compétences numériques, aptitudes visuospatiales),
- les usages effectifs des technologies (engagement, stratégies d'utilisation).

Plus spécifiquement, cette hypothèse générale implique que :

- les effets des dispositifs numériques varient en fonction du contexte pédagogique dans lequel ils sont implémentés ;
- les caractéristiques individuelles des apprenants modulent l'efficacité des environnements numériques ;

- les usages effectifs constituent un facteur médiateur central entre les dispositifs et les résultats d'apprentissage.

5 MODELE CONCEPTUEL

La question de recherche principale et l'hypothèse qui en découle ont conduit à l'élaboration d'un modèle conceptuel reposant sur l'idée que l'apprentissage médiatisé par le numérique ne peut être expliqué par un facteur isolé. Dans la continuité des cadres théoriques mobilisés précédemment, ce modèle s'inscrit dans une perspective interactionniste, selon laquelle les effets du numérique émergent de l'interaction dynamique entre plusieurs dimensions complémentaires.

Plus précisément, ce modèle vise à opérationnaliser les dimensions structurelle, individuelle et processuelle identifiées dans le cadrage théorique, en les articulant au sein d'un cadre analytique unifié. Il propose ainsi de dépasser une lecture technocentrée des dispositifs numériques pour analyser les conditions d'efficacité de l'apprentissage en anatomie. Le modèle repose sur trois dimensions principales.

5.1 Une dimension structurelle

La dimension structurelle renvoie aux contextes pédagogiques et aux caractéristiques des dispositifs d'apprentissage. Elle englobe notamment les modalités pédagogiques mises en œuvre (par exemple, la manipulation d'un modèle physique versus l'utilisation d'un environnement virtuel), le niveau d'interactivité proposé (passif, interactif ou immersif), ainsi que le contexte institutionnel dans lequel s'inscrit l'enseignement, en l'occurrence en Belgique et en République Démocratique du Congo.

Cette dimension correspond à l'architecture externe du système d'apprentissage et conditionne les possibilités d'action offertes aux apprenants.

5.2 Une dimension individuelle

La dimension individuelle concerne les profils des apprenants. Elle prend en compte, en particulier, leurs compétences numériques disciplinaires en anatomie ainsi que leurs aptitudes visuo-spatiales.

Elle vise à caractériser les ressources cognitives et dispositionnelles mobilisées par les étudiants dans leurs interactions avec les environnements numériques, en reconnaissant que les apprenants ne sont pas des utilisateurs homogènes des dispositifs.

5.3 Une dimension processuelle

La dimension processuelle porte sur les usages effectifs des outils numériques, tels qu'observés, par exemple, à travers l'utilisation de l'outil ARAnatomy. Elle s'intéresse à l'intensité des usages, au niveau d'engagement et aux dimensions motivationnelles associées.

Cette dimension permet de saisir l'apprentissage en train de se faire, à partir de l'analyse des comportements réels des apprenants, notamment via les traces d'activité issues des environnements numériques.

5.4 Articulation des dimensions

Ces trois dimensions fonctionnent en interaction étroite et dynamique. Les résultats d'apprentissage ne peuvent être attribués ni exclusivement au dispositif pédagogique, ni uniquement au profil de l'apprenant, ni seulement aux modalités d'usage ; ils émergent de la combinaison de ces facteurs et de leurs interactions.

Ainsi, le modèle repose sur une conception non linéaire et systémique de l'apprentissage, dans laquelle les effets observés résultent d'interactions complexes entre contexte, individu et usage, plutôt que d'un effet direct et isolé d'un facteur unique.

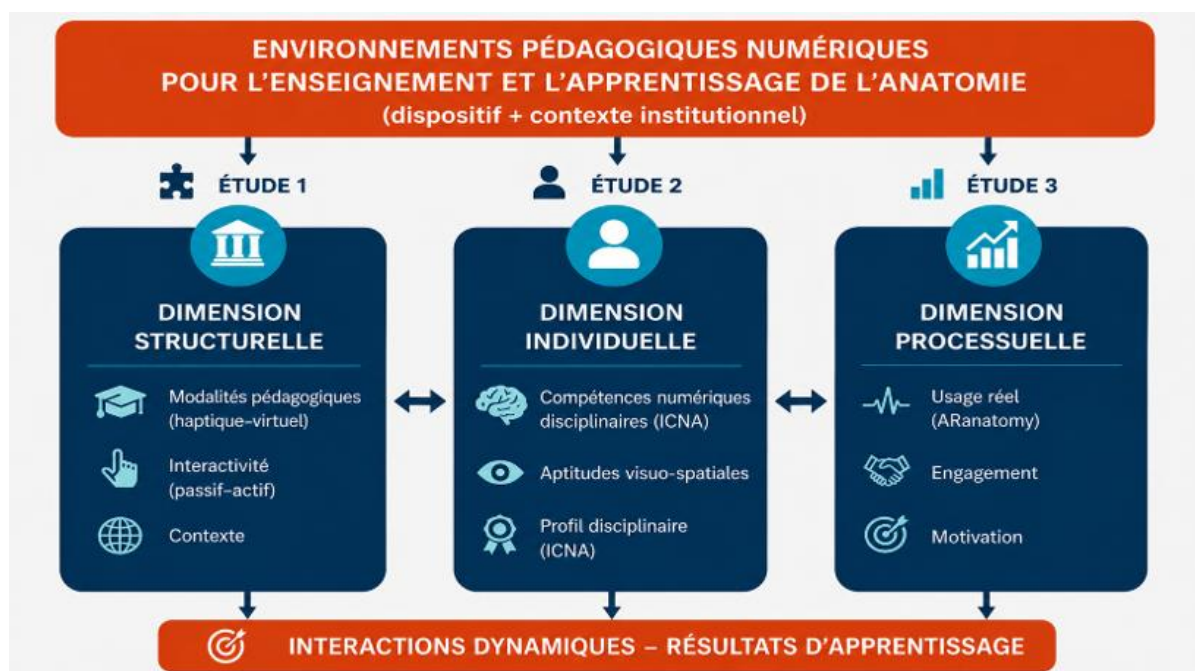


Figure 1. Modèle conceptuel des déterminants contextuels, individuels et processuels de l'apprentissage de l'anatomie numérique

Ce modèle constitue une proposition analytique visant à rendre compte des conditions d'efficacité des environnements numériques en anatomie. Il ne se substitue pas aux modèles existants, mais s'inscrit dans une logique de complémentarité, en proposant une lecture intégrative centrée sur l'interaction entre dimensions structurelles, individuelles et processuelles, particulièrement pertinente dans des contextes pédagogiques et institutionnels contrastés.

SECTION II – ANALYSE MULTINIVEAUX DE L'APPRENTISSAGE EN ANATOMIE NUMERIQUE : DU CONTEXTE AUX USAGES

Etude 1 — Analyse des dimensions structurelles des dispositifs numériques en anatomie

Préambule

Ce premier niveau s'intéresse aux conditions structurelles dans lesquelles les dispositifs pédagogiques sont déployés, en intégrant à la fois les modalités d'enseignement et les contextes institutionnels. Il vise à comprendre dans quelle mesure ces éléments influencent les effets observés sur l'apprentissage, indépendamment des caractéristiques individuelles des apprenants et de leurs usages effectifs.

Cette dimension structurelle est analysée dans cette **étude préliminaire** expérimentale multicentrique menée dans des contextes institutionnels contrastés — en Belgique et en République Démocratique du Congo — incluant à la fois des cursus universitaires et des formations professionnalisantes de type haute école. Il examine l'effet combiné des modalités pédagogiques (notamment virtuelles versus haptique, passives versus actives) et du contexte sur les apprentissages.

Plus spécifiquement, l'étude analyse les effets de ces dispositifs sur deux dimensions complémentaires : les performances en anatomie et le développement des aptitudes visuospatiales, reconnues comme centrales dans l'apprentissage des structures anatomiques.

En s'inscrivant dans une approche non techno-centrique, cette étude interroge l'hypothèse selon laquelle les technologies numériques produiraient des effets homogènes sur l'apprentissage.

Ainsi, cette première contribution constitue le niveau macro d'analyse de la thèse et pose les bases d'une compréhension contextualisée des effets du numérique en anatomie, en cohérence avec l'hypothèse centrale selon laquelle ces effets émergent de l'interaction entre contexte, profil et usage.

Projet d'article: ***“How, Who, Where—and When—Shape Anatomy Learning:
An Interactionist Multicenter Study Across Europe and Sub-Saharan Africa”***.

TITLE:

How, Who, Where—and When—Shape Anatomy Learning: An Interactionist Multicenter Study Across Europe and Sub-Saharan Africa

AUTHORS:

David Mutombo Mwembo, Pierre Bonnet, Olivier Prygiel, Allyson Fries, Elodie Nemery, Dimitri Kanyanda Nafatalewa, Willy Arung Kalau, Aude Lagier, Ninon Puttaert, Valérie Defaweux

ABSTRACT

Background

The educational effectiveness of digital anatomy learning modalities remains inconsistently reported across the literature. While immersive and interactive technologies may enhance engagement and visualization, their educational effects appear strongly influenced by learner-related, contextual, and temporal factors. This multicenter study investigated anatomy learning beyond a strictly technocentric perspective by examining how pedagogical modality, learner profile, institutional context, and temporality interact to shape learning outcomes.

Methods

A multicenter comparative study was conducted across three institutions located in Belgium and the Democratic Republic of the Congo. Undergraduate healthcare students without prior formal exposure to duodenopancreatic anatomy were randomly assigned to four pedagogical conditions combining modality (physical versus virtual) and interactivity (passive versus active): Virtual Passive (VP), Virtual Active (VA), Physical Passive (PP), and Physical Active (PA). The study integrated four complementary analytical dimensions: pedagogical modality (HOW), learner profile (WHO), institutional context (WHERE), and temporality of assessment (WHEN). Learner-related variables included self-reported digital competence in anatomy and visuospatial ability. Anatomical performances were assessed immediately after the intervention, after 24 hours, and during medium-term certificating examinations when available.

Results

Baseline learner profiles differed substantially across institutional cohorts, particularly regarding digital competence in anatomy (up to $d = 1.58$) and visuospatial ability (up to $d = 1.74$). A significant overall group effect was observed for immediate anatomical identification performance, with the active virtual condition showing higher immediate performance than passive conditions. However, these differences became markedly attenuated after 24 hours and were no longer detectable in medium-term certificating examination performance ($F(3,431) = 0.191$; $p = .902$). Delayed retention appeared more strongly associated with institutional cohort and learner-related variables than with pedagogical modality itself. Self-reported digital competence demonstrated a moderate positive association with delayed retention ($r = .41$, $p < .001$).

Conclusions

These findings support an interactionist interpretation of anatomy learning in which pedagogical modality, learner profile, institutional context, and temporality dynamically interact to shape educational outcomes. Although interactive virtual environments may facilitate immediate factual anatomical learning, their effectiveness appears highly dependent on contextual and learner-related conditions. Optimizing anatomy education may therefore require greater attention to educational ecosystems and longitudinal reinforcement processes rather than exclusive focus on technological modality alone.

Keywords

Anatomy education; Comparative study; educational technology; interactionist learning.

INTRODUCTION

Anatomy remains one of the foundational pillars of medical education and continues to play a central role in the development of clinical reasoning, surgical understanding, and spatial interpretation skills required for healthcare practice (Pawlina & Drake, 2016). Beyond simple memorization of structures, anatomy learning requires learners to mentally integrate complex three-dimensional relationships while simultaneously mobilizing cognitive, perceptual, and procedural processes relevant to clinical reasoning and surgical practice (Sugand et al., 2010).

However, anatomy teaching has undergone profound transformations over recent decades, particularly following reductions in cadaveric exposure, increasing student cohorts, curricular compression, and the rapid expansion of digital educational technologies (Aziz et al., 2002; Estai & Bunt, 2016). These evolutions have progressively shifted anatomy education from predominantly cadaver-based instruction toward multimodal and technology-enhanced pedagogical environments.

In response to these challenges, anatomy education has progressively integrated a wide range of digital and immersive learning environments, including three-dimensional visualization platforms, virtual dissection systems, augmented reality, haptic simulation, serious games, and interactive mobile applications (Nicholson et al., 2006; Moro et al., 2017; Adnan & Xiao, 2023). These technologies are frequently presented as innovative alternatives capable of improving visualization, learner engagement, spatial understanding, autonomy, and accessibility to anatomical resources (Ruiz et al., 2006; Bork et al., 2019).

Several theoretical frameworks have been proposed to explain the educational value of such technologies. Cognitive theories of multimedia learning suggest that combining visual, spatial, and interactive information may facilitate mental integration of complex anatomical representations (Mayer, 2009). Similarly, active learning approaches emphasize the importance of learner engagement and manipulation during encoding processes (Prince, 2004). In anatomy specifically, interactive exploration may support the construction of spatial mental models required for understanding intricate anatomical regions (Tam et al., 2009).

Nevertheless, the educational effectiveness of digital anatomy technologies remains inconsistently reported across the literature. While several studies describe positive effects on motivation, satisfaction, engagement, or short-term academic performance, others report limited or highly variable impacts on long-term retention and deeper conceptual learning (Kirkwood & Price, 2014; Triepels et al., 2020). Systematic reviews have further suggested that technological

innovation alone does not automatically guarantee improved educational outcomes (Moro et al., 2021).

Such inconsistencies suggest that anatomy learning outcomes may not depend exclusively on the technological modality itself. Increasing evidence indicates that educational technologies interact strongly with learner-related characteristics, contextual conditions, and temporal dimensions of learning (Cook et al., 2013; Ellaway & Bates, 2015). Digital competence and visuospatial ability appear to influence how students navigate, interpret, and mobilize complex anatomical representations within digital environments (Vorstenbosch et al., 2013). Students with stronger visuospatial abilities may more easily manipulate three-dimensional anatomical relationships, whereas digital competence may shape learners' capacity to efficiently engage with Technology-Enhanced learning environments.

Institutional conditions may also substantially shape the educational effects of anatomy technologies. Access to technological infrastructure, pedagogical support, curricular organization, class size, educational culture, and prior familiarity with digital learning environments may influence how students interact with anatomy learning tools (Ellaway & Bates, 2015; Frenk et al., 2010). These differences become particularly apparent when comparing highly contrasted educational environments, ranging from well-resourced European institutions with extensive technological and pedagogical infrastructures to universities enrolling several thousand students in contexts where access to anatomical and digital resources remains more limited. In such situations, institutional context may influence learning outcomes as much as the pedagogical modalities themselves.

At the same time, temporality represents another essential but frequently underestimated dimension of anatomy learning. Immediate post-intervention performance may not necessarily reflect durable anatomical retention. Research on retrieval practice, spaced learning, and consolidation processes consistently suggests that long-term retention depends not only on instructional format but also on repeated opportunities for reinforcement and reactivation over time (Cepeda et al., 2006; Karpicke & Blunt, 2011; Brown et al., 2014).

Taken together, these observations support a more interactionist interpretation of anatomy learning, in which pedagogical modality, learner characteristics, institutional context, and temporality dynamically interact rather than operate independently. However, few multicenter studies have simultaneously explored these dimensions within contrasted educational environments, particularly across Europe and Sub-Saharan Africa.

To address this gap, the present multicenter study investigated anatomy learning across three institutions located in Belgium and the Democratic Republic of the Congo. These included a university medical school (University of Liège), a professionally oriented higher education institution (Haute École de la Province de Liège), and a medical school enrolling particularly large student cohorts (University of Lubumbashi). This institutional diversity provided a unique opportunity to examine how pedagogical modalities operate across educational environments characterized by markedly different resources, pedagogical cultures, and organizational realities.

The duodenopancreatic frame was selected as the experimental anatomical model because of its high three-dimensional complexity, dense vascular and visceral organization, and major relevance in abdominal surgery (Triantafyllou et al., 2025).

Its anatomical complexity also derives from embryological rotation and fusion processes, making progressive constructive visualization particularly relevant for understanding its three-dimensional organization (Moore et al., 2023).

Participants were randomly assigned to four pedagogical conditions crossing modality (physical versus virtual) and interactivity (passive versus active).

Rather than seeking to identify a universally superior pedagogical modality, this study aimed to explore anatomy learning as the result of interactions between pedagogical conditions, learner characteristics, institutional context, and temporality of assessment. More specifically, the study investigated how digital competence in anatomy and visuospatial ability influenced immediate learning, delayed retention, and medium-term certificating performance across contrasted educational ecosystems.

MATERIALS AND METHODS

Study design

This multicenter comparative study investigated how pedagogical modality, learner profile, institutional context, and temporality interact to shape anatomy learning outcomes.

The study was conducted across three contrasted educational institutions located in Belgium and the Democratic Republic of the Congo: the University of Liège (ULiège), the Haute École de la Province de Liège (HEPL), and the University of Lubumbashi (UNILU).

The multicenter design was intentionally developed to explore anatomy learning under contrasted educational ecosystems characterized by differences in institutional environments, curricular organization, technological exposure, and pedagogical conditions. Such an approach allowed examination of the contextual variability potentially influencing the educational effects of anatomy learning modalities.

The experimental framework integrated four complementary analytical dimensions:

(1)	pedagogical	modality	(HOW),
(2)	learner-related	characteristics	(WHO),
(3)	institutional	context	(WHERE),

and (4) temporality of assessment (WHEN).

Pedagogical modality and institutional cohort constituted the principal independent variables, whereas anatomical learning performances represented the dependent variables. This multicenter comparative study was conducted within the framework of routine instructional activities rather than as a controlled experimental intervention. Consequently, all students received pedagogical support, as withholding anatomy instruction from a subset of learners solely to create a no-intervention control group was considered educationally inappropriate and inconsistent with principles of equitable teaching. The objective of the study was therefore to compare different pedagogical modalities rather than to evaluate learning against absence of instruction.

Study setting and Participants

Participants consisted of undergraduate healthcare students enrolled in anatomy-related curricula across the participating institutions, including first-year medical students at ULiège, first-year medical imaging students at HEPL, and second-year medical students at UNILU.

Recruitment was conducted during scheduled educational activities within each institution.

Only students without prior formal exposure to the anatomy of the duodenopancreatic frame were included in the study in order to minimize baseline knowledge disparities related to the experimental anatomical region.

Baseline variables included institutional affiliation, self-reported digital competence in anatomy, and visuospatial ability. Institutional affiliation was considered a contextual variable, whereas digital competence and visuospatial ability were analyzed as learner characteristics potentially influencing anatomy learning performance.

Table 1. Characteristics of participants across the three institutional cohorts

Institution	Country	Program	Academic Year	n	Mean age $\pm$ SD
ULiège	Belgium	Medicine	Year 1	54	20.8 $\pm$ 2.4 years
HEPL	Belgium	Medical Imaging	Year 1	457	21.3 $\pm$ 2.9 years
UNILU	DRC	Medicine	Year 2	432	20.3 $\pm$ 3.2 ans

Inclusion criteria were: (1) enrolment in one of the participating academic programs, (2) attendance at the learning session, and (3) absence of prior formal teaching on the duodenopancreatic frame. Exclusion criteria included incomplete datasets and missing assessment measures. Analyses involving certificating examination performance were restricted to students from Université de Liège, where this assessment was exclusively implemented.

Ethics approval and informed consent

Participants received an information and consent notice adapted from the standard ethical and data protection procedures of the University of Liège. Participation was voluntary, and submission of the questionnaire was considered as informed consent to participate. Data were anonymized prior to analysis and processed in accordance with the European General Data Protection Regulation (GDPR, EU 2016/679).

Pedagogical Design and experimental conditions (Figure 1)

Educational objectives

The intervention was designed to support two complementary learning objectives related to the anatomy of the duodenopancreatic frame: (1) identification of the principal anatomical structures and (2) understanding of three-dimensional anatomical relationships between digestive, biliary, pancreatic, and vascular components. These objectives were identical across all pedagogical conditions and constituted the educational framework underlying the learning activities.

Anatomical Learning Model

To ensure reproducibility across contrasted educational environments, a standardized anatomical learning model of the duodenopancreatic frame was developed by the Human Anatomy Laboratory of the University of Liège. The model was intentionally designed using low-cost assembly materials that are readily available in both European and Sub-Saharan African educational environments.

The model was organized into seven successive construction stages, each progressively introducing additional anatomical structures and progressively increasing the complexity of the representation. This sequential approach aimed to facilitate spatial integration and support the development of coherent mental representations of the anatomical region.

Each of the seven successive construction stages of the physical model was independently digitized using photogrammetry. The resulting virtual models reproduced the same progressive anatomical assembly sequence as the physical intervention, ensuring consistency of anatomical content and learning progression across physical and virtual conditions.

The three-dimensional virtual model of the duodenopancreatic frame was derived from a handcrafted anatomical model specifically created for this study. The physical prototype measured approximately 30–35 cm in length, 20–25 cm in height, and 12–15 cm in width, and was digitized through a photogrammetry workflow involving sequential image capture from multiple angles under standardized lighting conditions. The acquired images were processed using SketchNote3D® (licensed through the University of Liège and the Université du Québec à Trois-Rivières) to reconstruct a textured three-dimensional model. The resulting model was subsequently optimized and integrated into the interactive learning platform, allowing rotation, zooming, and progressive visualization of the seven construction steps.

Experimental Conditions (VP, PP, VA, PA)

The four pedagogical conditions combined modality (physical versus virtual) and interactivity (passive versus active): Virtual Passive (VP), Virtual Active (VA), Physical Passive (PP), and Physical Active (PA).

In the passive virtual (VP) condition, students successively observed static digital representations corresponding to the seven progressive construction stages of the anatomical model without direct manipulation.

In the passive physical (PP) condition, learners successively explored the seven construction stages using tangible anatomical material under teacher guidance without actively modifying the assembly.

In the active virtual (VA) condition, participants successively interacted with seven three-dimensional virtual construction stages allowing rotation, zooming, and dynamic exploration of anatomical structures.

The virtual model was hosted on the Sketchfab platform and made available to participants through a QR code accessible on personal mobile devices. Students could access the model using a smartphone or tablet connected to the internet.

In the active physical (PA) condition, students progressively assembled the anatomical model themselves through the same seven successive construction stages.

All groups received identical learning objectives and were exposed to the same anatomical content related to the duodenopancreatic region.

In passive conditions, students primarily observed the anatomical material under teacher guidance without direct manipulation, whereas active conditions allowed learners to manipulate, explore, and interact directly with the anatomical environment. Virtual conditions relied on three-dimensional digital anatomical representations, while physical conditions used tangible anatomical material and physical models.

All sessions were supervised by anatomy instructors under standardized pedagogical conditions to reduce instructional variability between groups.

Randomization Procedure

Following informed consent, participants were randomly assigned to one of the four pedagogical conditions prior to the learning session using a simple random allocation procedure performed by the principal investigator. Randomization was conducted separately within each institutional cohort in order to minimize institutional imbalance across pedagogical conditions. Group distributions remained globally comparable across cohorts regarding baseline visuospatial ability and self-reported digital competence in anatomy.

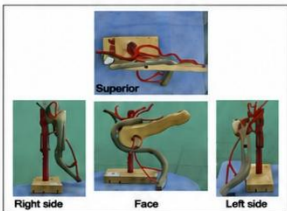
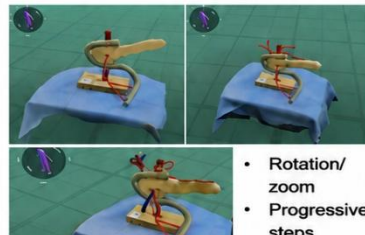
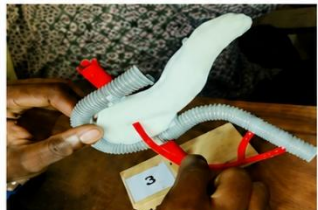
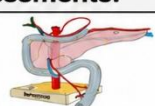
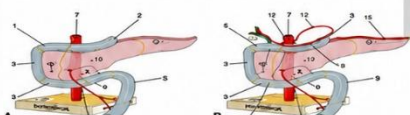
Experimental pedagogical modalities for the construction of the duodenopancreatic frame	
Passive	Active
V I R T U A L Static Images  Static images	Interactive 3D models  - Rotation/zoom - Progressive steps
P H S I C A L Observation only  Fully assembled model	Hands-on assembly  Step-by-step construction
Examples of items included in the immediate and delayed assessments.	
 Choose a cross-section 	Visuospatial task Section-interpretation task: participants identified the anatomical plane and corresponding structures on 2D slices.
	Identification task Factual knowledge task : identifying annotated anatomical structures.

Figure 1. Experimental pedagogical modalities and assessment framework for learning the duodenopancreatic anatomy.

Overview of the four pedagogical modalities used to teach the duodenopancreatic anatomy, combining virtual versus physical and passive versus active approaches. The lower panel presents examples of visuospatial and anatomical identification tasks used in the immediate and delayed assessments.

Learner-related variables

Self-reported digital competence in anatomy

Self-reported digital competence in anatomy was assessed using the ICNA instrument (Indice de Compétence Numérique en Anatomie), a discipline-specific instrument developed and validated by our research team to evaluate students' perceived ability to mobilize digital resources within anatomy learning environments. The original French title of the instrument was intentionally

retained because the tool was initially conceptualized and developed in French before being translated into English. The instrument explored dimensions related to perceived utility, digital tool use, self-efficacy, and engagement with technology-enhanced learning.

The final validated version retained 37 items organized into five dimensions. Responses were recorded using a Likert-type scale, with higher scores reflecting higher perceived digital competence in anatomy. Internal consistency analyses demonstrated satisfactory to excellent reliability across dimensions (Cronbach's α ranging from .60 to .97). The development and psychometric validation of the ICNA instrument have been reported elsewhere (manuscript submitted to *Anatomical Sciences Education*, March 19, 2026).

Visuospatial ability

Visuospatial ability was evaluated using the Mental Rotation Test (MRT), administered under standardized timed conditions consisting of two consecutive three-minute sessions. The MRT evaluates participants' capacity to mentally manipulate and compare three-dimensional objects and is widely recognized as a valid measure of spatial ability in anatomy education research (Vandenberg & Kuse, 1978; Nguyen et al., 2022). The version used in this study comprised 24 items divided into two sets of 12, with a maximum possible score of 24. A response was considered correct only when the two matching rotated figures were accurately identified.

Outcome Measures

The two learning outcomes (anatomical structures identification and three-dimensional anatomical relationships understanding) were evaluated.

Identification

Anatomical identification performance was assessed through a structured exercise involving 21 anatomical structures of the duodenopancreatic frame. Participants were required to identify major digestive, biliary, pancreatic, and vascular components presented within the anatomical model. The selected structures were specifically defined by the Human Anatomy Laboratory of the University of Liège to reflect both the educational objectives of the intervention and the progressive organization of the model. Individual identifications were aggregated into a composite anatomical identification score reflecting factual anatomical knowledge and recognition accuracy across the anatomical region.

Visuospatial

Visuospatial performance was assessed through a set of anatomical interpretation tasks based on successive anatomical views and sectional representations of the duodenopancreatic frame. Participants were required to analyze spatial relationships between structures and infer their three-dimensional organization from different observational perspectives. These tasks were designed to evaluate spatial reasoning and mental reconstruction abilities in a complex anatomical environment.

Temporality of Assessment

Anatomical performances were assessed at three complementary time points to distinguish immediate learning effects from delayed consolidation processes: (1) immediate post-intervention evaluation, (2) delayed retention assessment after 24 hours, and (3) medium-term certificating examination performance when available. The 24-hour interval was intentionally selected to explore early consolidation processes and short-term retention beyond immediate post-intervention performance while minimizing the influence of longer-term curricular exposure and external reinforcement (Dudai, 2004; Cepeda et al., 2006).

The immediate assessment included seven visuospatial items and one complex anatomical identification task involving 21 structures related to duodenopancreatic anatomy. The delayed assessment consisted of a 22-item evaluation composed of 12 visuospatial items (items 1–12) and 10 factual anatomical identification items (items 13–22), allowing evaluation of short-term knowledge retention after initial consolidation. The immediate and delayed assessments were not identical but explored comparable anatomical content and cognitive dimensions. In both assessments, visuospatial items were presented before factual identification tasks. Medium-term academic performance was assessed using selected items from the regular certificating anatomy examination completed at Université de Liège, the only institution where the duodenopancreatic frame was formally included in the official curriculum examination. This final assessment was intended to explore the persistence of educational effects under authentic certificating academic conditions.

Reliability measurements were not calculated for the certificating anatomy examination because this examination was not designed as a unidimensional psychometric instrument. It consisted of a routine anatomy assessment covering multiple anatomical regions and learning objectives rather than a test focused exclusively on the duodenopancreatic frame. Consequently, internal consistency indices would have limited interpretability in this context.

Statistical analysis

Data preprocessing and organization were performed using Microsoft Excel (Microsoft 365), and all statistical analyses were conducted using Jamovi software version 2.6.44 (The Jamovi Project, Sydney, Australia), which interfaces with R statistical computing libraries.

Descriptive statistics were calculated for all study variables and are reported as means, standard deviations, frequencies, percentages, or 95% confidence intervals where appropriate. Internal consistency of questionnaire-based measures was evaluated using Cronbach's alpha coefficients.

Prior to inferential analyses, assumptions of normality and homogeneity of variances were assessed using Shapiro–Wilk tests, visual inspection of Q-Q plots, and Levene's tests, respectively. Group comparisons were primarily conducted using one-way or two-way analyses of variance (ANOVA), according to the structure of the variables analyzed. When significant overall effects were identified, post hoc comparisons were performed using Tukey-adjusted tests. Effect sizes were reported using Cohen's *d* and partial eta squared (η^2_p) where appropriate.

Associations between learner-related variables (digital competence and visuospatial ability) and anatomical learning outcomes were explored using Pearson correlation analyses, partial

correlations, and linear regression models. Chi-square analyses were additionally used for categorical comparisons when appropriate.

The analytical strategy was designed not only to compare pedagogical modalities, but also to explore how learner characteristics, institutional context, and temporality of assessment interacted to influence anatomy learning outcomes across immediate, delayed, and medium-term evaluations. Statistical significance was established at $p < .05$.

RESULTS

Baseline learner profiles across institutional cohorts

Baseline learner characteristics differed substantially across participating institutions. Students from UNILU reported markedly higher self-reported digital competence in anatomy than those from HEPL ($d = -1.58$) and ULiège ($d = -1.05$), whereas ULiège students demonstrated the highest visuospatial ability, significantly outperforming both UNILU ($d = 1.74$) and HEPL ($d = -1.20$) cohorts (all $ps < .001$, except HEPL vs UNILU for VSA: $p = .767$).

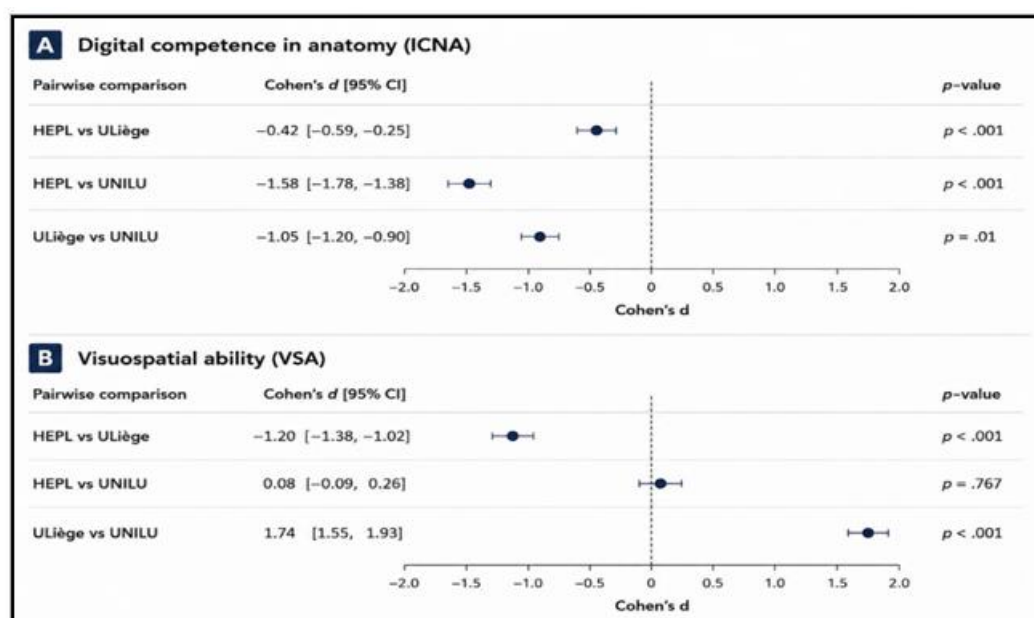


Figure 2. Pairwise effect size comparisons of digital competence in anatomy and visuospatial ability across institutional cohorts.

Forest-style representation of Cohen's d effect sizes for pairwise comparisons between institutions regarding self-reported digital competence in anatomy (A) and visuospatial ability (B). Horizontal lines represent 95% confidence intervals. Negative and positive values indicate the direction and magnitude of inter-institutional differences. The vertical dashed line corresponds to the null effect ($d = 0$).

Baseline equivalence of experimental groups

To ensure the internal validity of the study, baseline equivalence analyses were conducted across the four pedagogical groups within institutional cohorts. Comparisons based on visuospatial ability and self-reported digital competence in anatomy (ICNA) revealed no statistically significant baseline differences between experimental conditions prior to the intervention (all p s $> .05$). These findings suggest that subsequent differences in learning performances were unlikely to result from pre-existing disparities between groups and support the adequacy of the randomization procedure.

Performance on the anatomical identification task across pedagogical modalities.

Immediate anatomical identification performance was assessed using a structured identification task involving 21 anatomical structures of the duodenopancreatic frame.

A significant overall group effect was observed.

The active virtual group (VA) achieved the highest mean score (mean ≈ 3.2), significantly outperforming the passive physical group (PP), which showed the lowest performance (mean ≈ 1.1). Intermediate scores were observed for the passive virtual (VP; ≈ 2.4) and active physical (PA; ≈ 1.5) conditions.

Post hoc analyses confirmed superior immediate identification performance in the active virtual condition compared with passive physical and active physical modalities (p s $< .001$; $d = .37-.46$).

However, these differences remained globally limited across the broader learning outcomes, and no single pedagogical modality consistently outperformed all others. (Figure 3).

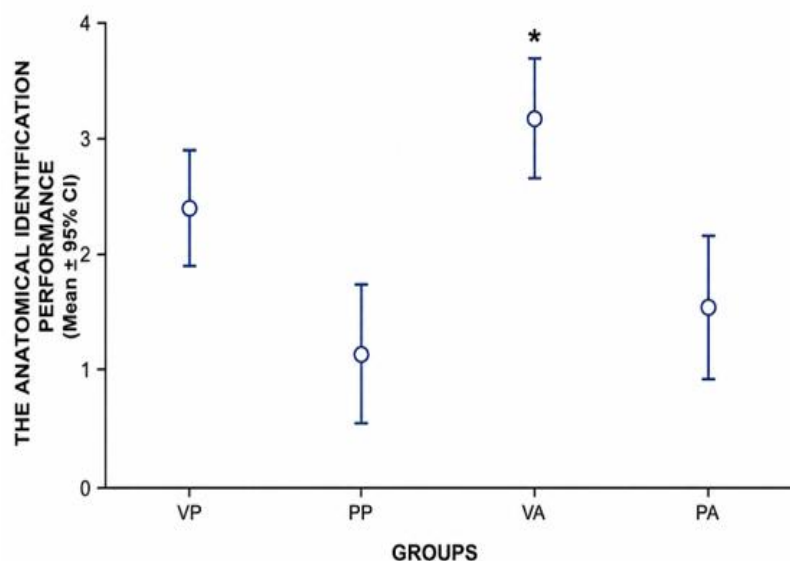


Figure 3. Immediate anatomical identification performance across pedagogical modalities.

Mean scores ($\pm$ 95% confidence intervals) obtained on the anatomical identification task involving 21 anatomical structures of the duodenopancreatic frame. The Virtual Active (VA) condition demonstrated significantly higher immediate factual anatomical performances. VP = Virtual Passive; PP = Physical Passive; VA = Virtual Active; PA = Physical Active. $*p < .001$.

Delayed retention after 24 hours

Differences observed during immediate assessment became markedly attenuated after 24 hours. Delayed retention scores remained globally comparable across pedagogical modalities for both Delayed visuospatial retention scores and Delayed anatomical identification retention scores, with group means clustering around 4/12 and 3/10, respectively. No clear superiority of any modality was observed at delayed testing, despite the short-term advantage initially noted in the active virtual condition (Figure 4).

In contrast, delayed performances appeared more strongly associated with institutional cohort and learner-related factors than with pedagogical modality itself. Large interinstitutional differences in baseline learner profiles were observed, particularly for visuospatial ability (up to $d = 1.74$) and digital competence in anatomy (up to $d = 1.58$), whereas delayed retention scores remained globally comparable across pedagogical modalities. These findings support a contextualized and interactionist interpretation of anatomy learning.

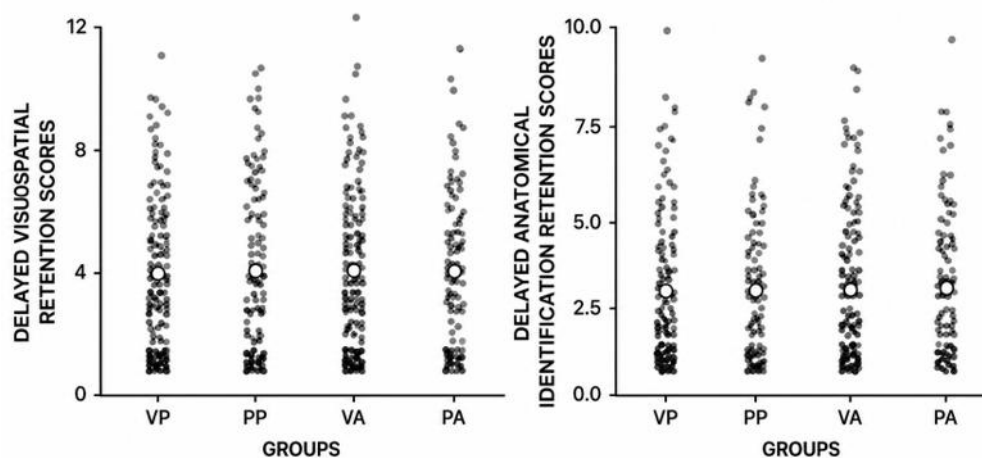


Figure 4. Delayed retention performances across pedagogical modalities after 24 hours.

Distribution of delayed retention scores according to the four pedagogical modalities 24 hours after the intervention. The left panel represents delayed visuospatial anatomical performance, whereas the right panel represents delayed factual anatomical performance. White circles indicate group mean scores. No major persistent differences between pedagogical modalities were observed after delayed assessment. VP = Virtual Passive; PP = Physical Passive; VA = Virtual Active; PA = Physical Active.

Associations between learner characteristics and delayed retention Self-reported digital competence in anatomy (ICNA) demonstrated a moderate positive association with delayed retention performance ($r = .41$, $p < .001$). Visuospatial ability (VSA) was also positively associated with delayed retention, although to a lesser extent ($r = .23$, $p = .018$). These findings suggest that learner-related characteristics may contribute differently to anatomy learning retention.

Medium-term certifying examination performance (ULiège)

No significant differences were observed between pedagogical groups regarding medium-term certifying examination performance within the ULiège cohort. Although success rates numerically varied across modalities—ranging from 36.6% in the passive virtual group (VP) to 61.9% in the active physical group (PA), with intermediate rates of 45.3% (PP) and 45.6% (VA)—these differences did not reach statistical significance (Figure 5).

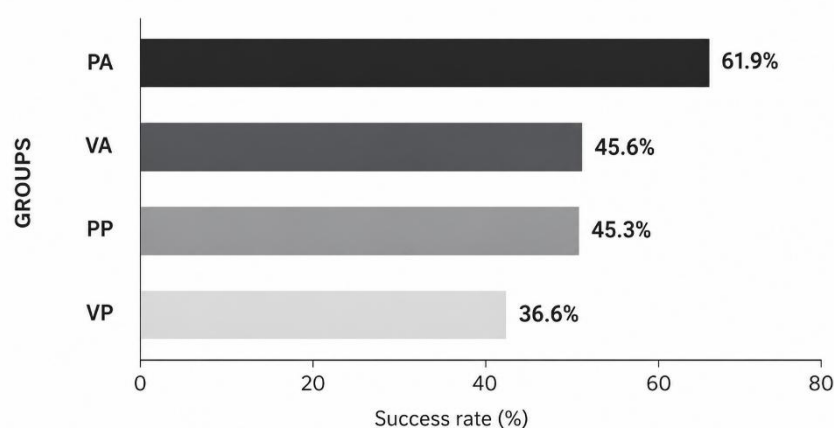


Figure 5. Medium-term certifying examination performance across pedagogical modalities (ULiège Cohort).

Success rates for the three duodenopancreatic examination questions according to the four pedagogical modalities among ULiège students. Although the Physical Active group demonstrated the highest success rate, no statistically significant difference was observed between groups (ANOVA: $F(3,431) = 0.191$; $p = .902$). VP = Virtual Passive; PP = Physical Passive; VA = Virtual Active; PA = Physical Active.

Variability Across Institutional Contexts

Considerable variability was observed across institutional cohorts and pedagogical conditions during the immediate anatomical identification assessment. Success rates ranged from 10.0% to 33.1% depending on the combination of institution and learning modality (Figure 6). The highest performance was observed in Group VA at ULiège (33.1%), whereas the lowest was recorded in Group VA at HEPL (10.0%). In contrast, Group PA showed relatively stable performances across the three institutions (25.0–25.8%).

These observations illustrate the heterogeneity of learning outcomes across educational contexts and suggest that the effectiveness of a given pedagogical modality may vary according to institutional environment. A significant association between institutional cohort and success rate distribution was observed ($\chi^2(2) = 6.64, p = .036$).

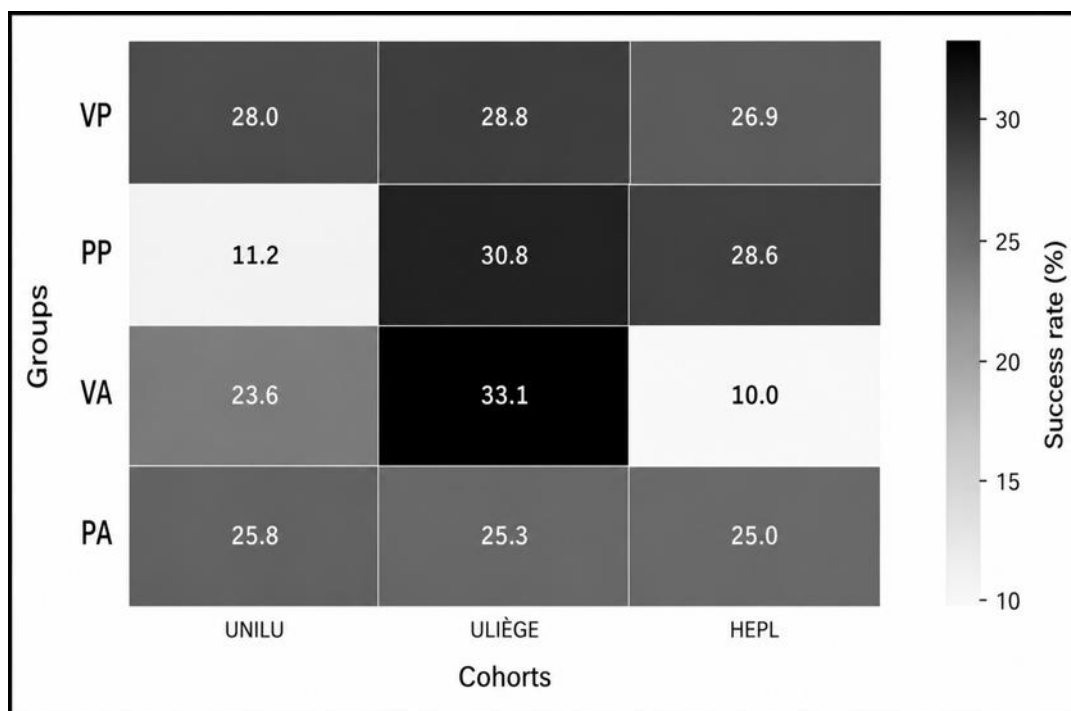


Figure 6. Variability in immediate anatomical identification performance across pedagogical modalities and institutional contexts.

Heatmap representing the proportion of correct responses obtained on the anatomical identification task across the four pedagogical conditions within each participating institution (ULIège, HEPL, and UNILU). Darker shades indicate higher success rates identification task across the four pedagogical conditions within each institutional cohort.

DISCUSSION

The present multicenter study sought to move beyond a strictly technocentric interpretation of anatomy education by examining how pedagogical modalities, learner characteristics, institutional context, and temporality of assessment interact to shape learning outcomes. Overall, our findings suggest that the observed performances cannot be explained by pedagogical modality alone and that the educational effects of digital technologies remain strongly dependent on learner-related characteristics, the contexts in which they are implemented, and the temporal conditions under which learning is evaluated.

A first important observation concerns the relatively limited influence of pedagogical modality itself. Although the active virtual condition demonstrated the highest performance during the

immediate anatomical identification task, this advantage remained restricted to the immediate evaluation and was no longer observed during delayed retention or certificating examination performance. No modality systematically outperformed the others across all evaluated outcomes. These findings align with a growing body of literature showing that digital and immersive technologies do not systematically produce superior anatomy learning outcomes compared with more traditional pedagogical approaches (Moro et al., 2021; Triepels et al., 2020). More broadly, Kirkwood and Price (2014) emphasized that the pedagogical benefits attributed to educational technologies often derive more from the learning activities they enable than from the technology itself. In this perspective, our findings suggest that pedagogical modality primarily influences how students engage in the learning activity without necessarily determining, by itself, the quality or durability of the acquired knowledge.

Nevertheless, the short-term advantage observed in the active virtual condition deserves further consideration. One possible explanation may reside in the exploratory affordances offered by the interactive digital model. Active manipulation of anatomical structures likely enhanced attentional engagement and facilitated spatial exploration during the encoding phase. The active virtual condition therefore appeared particularly advantageous for immediate factual identification tasks involving active exploration and rapid spatial integration. This interpretation is consistent with active learning theories emphasizing the importance of learner participation in knowledge construction processes (Prince, 2004), as well as with Mayer's multimedia learning theory (2009), according to which active integration of visual and spatial information promotes cognitive organization of complex content. However, the disappearance of this advantage after only 24 hours suggests that interactivity alone is insufficient to guarantee durable consolidation following a brief pedagogical intervention. This observation also supports critiques of deterministic approaches if increasing technological sophistication automatically results in superior learning outcomes (Cook et al., 2013).

Our findings also highlight the importance of learner-related characteristics. No significant differences in digital competence in anatomy or visuospatial ability were observed between the four pedagogical conditions prior to the intervention, supporting the comparability of the experimental groups. In contrast, significant differences emerged across the three institutional cohorts. Students from UNILU reported higher levels of digital competence in anatomy, whereas ULiège students demonstrated the strongest visuospatial performances. These differences should not be interpreted merely as methodological noise, but rather as educational variables in their own right. Students do not approach pedagogical environments with identical cognitive resources, prior experiences, or learning habits.

These findings further highlight the presence of heterogeneous learner profiles across educational environments before the intervention itself. Such differences support the hypothesis that institutional context and learner-related characteristics may substantially shape anatomy learning conditions independently of pedagogical modality alone.

While visuospatial ability has long been recognized as an important factor in anatomy learning (Tam et al., 2009; Vorstenbosch et al., 2013), our findings suggest that ICNA scores may be more strongly associated with delayed retention. This observation should nevertheless be interpreted cautiously. Unlike visuospatial ability, which reflects an objectively assessed cognitive capacity, the ICNA relies on self-reported perceptions of ease and confidence in mobilizing digital tools for anatomy learning. However, these findings suggest that students' perceived ability to effectively use anatomy-related digital resources may play an important role in their engagement with learning activities and, indirectly, in knowledge consolidation processes. This interpretation

aligns with previous work showing that digital learning environments strongly interact with individual learner characteristics rather than producing effects independently from them (Berney et al., 2015).

Perhaps the most important finding of this study concerns the influence of institutional context. Delayed retention performances appeared more strongly associated with institutional cohort than with pedagogical modality itself. Furthermore, the same pedagogical modality did not systematically produce identical performance profiles across institutions. These observations suggest that educational technologies cannot be interpreted independently from the socioeducational environments in which they are implemented. Pedagogical cultures, curricular organization, prior exposure to digital learning, educational support systems, and available technological infrastructures may all influence the ways students appropriate learning activities. This interpretation is consistent with research on Technology-Enhanced learning environments emphasizing their deeply contextual nature (Ellaway & Bates, 2015). In this perspective, institutional context does not merely represent the background of learning; it becomes one of its major determinants.

This contextual interpretation appears particularly relevant within the framework of a multicenter study conducted across contrasted educational ecosystems such as those represented here in Belgium and Sub-Saharan Africa. Rather than opposing “resource-rich” and “resource-limited” environments in a simplistic manner, our findings suggest that educational technologies dynamically interact with local educational realities, pedagogical cultures, and learner expectations. The effectiveness of a given modality therefore seems to depend less on its intrinsic characteristics than on the conditions under which it is implemented and supported.

The temporal dimension also emerged as a central element of interpretation. Although some differences between modalities appeared immediately after the intervention, these differences largely diminished after 24 hours and were no longer detectable during certificating assessment. These findings remind us that success on an immediate post-test cannot be equated with durable learning. Research on retrieval practice, spaced repetition, and consolidation mechanisms consistently demonstrates that long-term retention primarily depends on repeated opportunities for knowledge reactivation and reinforcement (Cepeda et al., 2006; Karpicke & Blunt, 2011; Brown et al., 2014). In this perspective, the limited persistence of modality-related effects observed in our study may simply reflect the fact that learning consolidation depends more strongly on subsequent educational experiences than on an isolated intervention.

Taken together, these findings support an interactionist interpretation of anatomy learning. The question is probably not whether virtual learning is superior to physical learning, nor whether active learning is intrinsically preferable to passive observation. Rather, the findings suggest that anatomy learning emerges from complex interactions between pedagogical modalities, learner characteristics, institutional contexts, and temporality. The educational value of digital technologies therefore appears less dependent on their intrinsic characteristics than on the conditions under which they are experienced, integrated, and reinforced.

From a pedagogical perspective, these findings encourage caution toward exclusively technology-centered approaches to anatomy education. The challenge may not be to identify a universally superior technology, but rather to understand which pedagogical strategies are best suited to specific learners within specific contexts. Future research may therefore benefit from shifting attention away from simple modality comparisons toward more integrative models simultaneously considering learner profiles, contextual variables, and longitudinal learning trajectories.

Limitations

Several limitations should be considered when interpreting these findings. First, the absence of baseline pretesting limits the possibility of fully controlling for initial differences between participants despite random allocation procedures. Second, the intervention consisted of a relatively brief educational exposure, which may partly explain the rapid attenuation of the observed effects. Third, although the multicenter design constitutes a major strength of the study, it also introduces contextual variability that remains difficult to control entirely. Finally, other variables potentially influencing learning outcomes, such as motivation, cognitive load, self-regulated learning strategies, or prior familiarity with digital anatomy tools, were not directly assessed and deserve further investigation in future studies. In addition, medium-term certificating performance was evaluated using a limited number of examination items specifically related to the duodenopancreatic frame, since the official anatomy examination covered multiple anatomical regions and broader curricular objectives.

CONCLUSION

This multicenter study conducted across Europe and Sub-Saharan Africa suggests that anatomy learning emerges from dynamic interactions between pedagogical modality, learner profile, institutional context, and temporality rather than from technology alone.

Although interactive virtual environments appeared associated with improved immediate factual anatomical identification, these advantages became markedly attenuated over time and did not translate into superior medium-term certificating performance following a single short intervention. In contrast, learner-related characteristics and institutional context appeared to exert a more persistent influence on delayed retention outcomes.

These findings challenge purely technocentric interpretations of anatomy education and support a more contextualized and interactionist understanding of digital learning environments. The educational value of anatomy technologies appears highly dependent on the conditions under which they are implemented, including learner preparedness, pedagogical support, institutional ecosystems, and opportunities for longitudinal reinforcement.

Consequently, optimizing anatomy learning may require less emphasis on identifying universally superior technologies and greater attention to how educational environments are structured, contextualized, and sustained over time.

Beyond modality alone, effective anatomy education may ultimately depend on understanding not only how students learn, but also who learns, where learning occurs, and when knowledge consolidation takes place.

REFERENCES

1. Adnan, S., & Xiao, J. (2023). A scoping review on the trends of digital anatomy education. *Clinical Anatomy*, 36(3), 471–491. <https://doi.org/10.1002/ca.23995>
2. Aziz, M. A., McKenzie, J. C., Wilson, J. S., Cowie, R. J., Ayeni, S. A., & Dunn, B. K. (2002). The human cadaver in the age of biomedical informatics. *The Anatomical Record*, 269(1), 20–32. <https://doi.org/10.1002/ar.10046>
3. Berney, S., Bétrancourt, M., Molinari, G. and Hoyek, N. (2015), How spatial abilities and dynamic visualizations interplay when learning functional anatomy with 3D anatomical models. *American Association of Anatomists*, 8: 452-462. <https://doi.org/10.1002/ase.1524>
4. Bork, F., Stratmann, L., Enssle, S., Eck, U., Navab, N., Waschke, J., & Kugelmann, D. (2019). The benefits of an augmented reality magic mirror system for integrated radiology teaching in gross anatomy. *Anatomical Sciences Education*, 12(6), 585–598. <https://doi.org/10.1002/ase.1864>
5. Brown, P. C., Roediger, H. L., III, & McDaniel, M. A. (2014). *Make it stick: The science of successful learning*. Harvard University Press.
6. Cepeda, N. J., Pashler, H., Vul, E., Wixted, J. T., & Rohrer, D. (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin*, 132(3), 354–380. <https://doi.org/10.1037/0033-2909.132.3.354>
7. Cook, D. A., Levinson, A. J., & Garside, S. (2013). Time and learning efficiency in Internet-based learning: A systematic review and meta-analysis. *Advances in Health Sciences Education*, 15(5), 755–770. <https://doi.org/10.1007/s10459-010-9231-x>
8. Dudai, Y. (2004). The neurobiology of consolidations, or, how stable is the engram? *Annual Review of Psychology*, 55, 51–86. <https://doi.org/10.1146/annurev.psych.55.090902.142050>
9. Ellaway, R. H., & Bates, J. (2015). Exploring patterns and pattern languages of medical education. *Medical Education*, 49(12), 1189–1196. <https://doi.org/10.1111/medu.12836>
10. Estai, M., & Bunt, S. (2016). Best teaching practices in anatomy education: A critical review. *Annals of Anatomy*, 208, 151–157. <https://doi.org/10.1016/j.aanat.2016.02.010>
11. Frenk, J., Chen, L., Bhutta, Z. A., Cohen, J., Crisp, N., Evans, T., Fineberg, H., Garcia, P., Ke, Y., Kelley, P., Kistnasamy, B., Meleis, A., Naylor, D., Pablos-Mendez, A., Reddy, S., Scrimshaw, S., Sepulveda, J., Serwadda, D., & Zurayk, H. (2010). Health professionals for a new century: Transforming education to strengthen health systems in an interdependent world. *The Lancet*, 376(9756), 1923–1958. [https://doi.org/10.1016/S0140-6736\(10\)61854-5](https://doi.org/10.1016/S0140-6736(10)61854-5)
12. Karpicke, J. D., & Blunt, J. R. (2011). Retrieval practice produces more learning than elaborative studying with concept mapping. *Science*, 331(6018), 772–775. <https://doi.org/10.1126/science.1199327>
13. Kirkwood, A., & Price, L. (2014). Technology-enhanced learning and teaching in higher education: What is “enhanced” and how do we know? A critical literature review. *Learning, Media and Technology*, 39(1), 6–36. <https://doi.org/10.1080/17439884.2013.770404>
14. Mayer, R. E. (2009). *Multimedia learning* (2nd ed.). Cambridge University Press. <https://doi.org/10.1017/CBO9780511811678>
15. Moore, K. L., Persaud, T. V. N., & Torchia, M. G. (2023). *The developing human: Clinically oriented embryology* (12th ed.). Elsevier.
16. Moro, C., Štromberga, Z., Raikos, A., & Stirling, A. (2017). The effectiveness of virtual and augmented reality in health sciences and medical anatomy. *Anatomical Sciences Education*, 10(6), 549–559. <https://doi.org/10.1002/ase.1696>
17. Moro, C., Birt, J., Stromberga, Z., Phelps, C., Clark, J., Glasziou, P. and Scott, A.M. (2021), Virtual and Augmented Reality Enhancements to Medical and Science Student Physiology

- and Anatomy Test Performance: A Systematic Review and Meta-Analysis. *Anatomical Sciences Education*, 14: 368-376. <https://doi.org/10.1002/ase.2049>
18. Nguyen, N., Mulla, A., Nelson, A. J., & Wilson, T. D. (2014). Visuospatial anatomy comprehension: The role of spatial visualization ability and problem-solving strategies. *Anatomical Sciences Education*, 7(4), 280–288. <https://doi.org/10.1002/ase.1415>
 19. Nicholson, D. T., Chalk, C., Funnell, W. R., & Daniel, S. J. (2006). Can virtual reality improve anatomy education? A randomised controlled study of a computer-generated three-dimensional anatomical ear model. *Medical Education*, 40(11), 1081–1087. <https://doi.org/10.1111/j.1365-2929.2006.02611.x>
 20. Pawlina, W., & Drake, R. L. (2016). Authentic learning in anatomy: A primer on pragmatism. *Anatomical Sciences Education*, 9(1), 5–7. <https://doi.org/10.1002/ase.1592>
 21. Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education*, 93(3), 223–231. <https://doi.org/10.1002/j.2168-9830.2004.tb00809.x>
 22. Ruiz, J. G., Mintzer, M. J., & Leipzig, R. M. (2006). The impact of e-learning in medical education. *Academic Medicine*, 81(3), 207–212. <https://doi.org/10.1097/00001888-200603000-00002>
 23. Sugand, K., Abrahams, P., & Khurana, A. (2010). The anatomy of anatomy: A review for its modernization. *Anatomical Sciences Education*, 3(2), 83–93. <https://doi.org/10.1002/ase.139>
 24. Tam, M. D. B. S., Hart, A. R., Williams, S., Holland, R. C., Heylings, D. J. A., & Leinster, S. J. (2009). Is learning anatomy facilitated by computer-aided learning? A review of the literature. *Medical Teacher*, 31(9), e393–e396. <https://doi.org/10.1080/01421590802650092>
 25. Triantafyllou, G., Lyros, O., Arkadopoulos, N., Kokoropoulos, P., Demetriou, F., Samolis, A., Olewnik, Ł., Landfald, I. C., & Piagkou, M. (2025). The blood supply of the human pancreas: Anatomical and surgical considerations. *Journal of Clinical Medicine*, 14(16), 5625. <https://doi.org/10.3390/jcm14165625>
 26. Triepels, C. P. R., Smeets, C. F. A., Notten, K. J. B., Kruitwagen, R. F. P. M., Fütterer, J. J., Vergeldt, T. F. M., & Van Kuijk, S. M. J. (2020). Does three-dimensional anatomy improve student understanding? *Clinical Anatomy*, 33(1), 25–33. <https://doi.org/10.1002/ca.23405>
 27. Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, 47(2), 599–604. <https://doi.org/10.2466/pms.1978.47.2.599>
 28. Vorstenbosch, M. A. T. M., Klaassen, T. P., Donders, A. R. T., Kooloos, J. G. M., Bolhuis, S. M., & Laan, R. F. J. M. (2013). Learning anatomy enhances spatial ability. *Anatomical Sciences Education*, 6(4), 257–262. <https://doi.org/10.1002/ase.1346>

**Etude 2— Niveau individuel :
Analyse des profits des apprenants
et des compétences numérique en
anatomie**

Préambule

Faisant suite à l'analyse des dimensions structurelles, la dimension individuelle s'intéresse aux caractéristiques des apprenants, et plus particulièrement aux compétences numériques qu'ils mobilisent dans les environnements d'apprentissage de l'anatomie.

Cette dimension renvoie à l'idée que les effets des dispositifs numériques ne peuvent être compris indépendamment des ressources individuelles des étudiants. En particulier, dans des environnements fortement médiatisés par des outils tridimensionnels, immersifs ou interactifs, la capacité à mobiliser des compétences numériques adaptées constitue une condition essentielle de l'engagement et de l'apprentissage.

L'analyse de cette dimension individuelle fait l'objet de l'**Article 1** qui vise à répondre à une limite importante de la littérature : l'absence d'instruments permettant d'évaluer de manière spécifique les compétences numériques mobilisées dans l'apprentissage de l'anatomie, les outils existants reposant majoritairement sur des cadres génériques peu sensibles aux pratiques technico-visuelles propres à cette discipline.

Pour répondre à cet enjeu, un instrument original — l'Indice de Compétences Numériques en Anatomie (ICNA) — spécifiquement conçu dans le cadre de cette recherche doctorale — a été développé et validé à partir d'un échantillon multicentrique de 774 étudiants issus de trois contextes institutionnels contrastés (Belgique et République Démocratique du Congo), incluant à la fois des cursus universitaires et des formations professionnalisantes.

Les analyses psychométriques mettent en évidence une structure multidimensionnelle des compétences numériques en anatomie, intégrant non seulement des dimensions techniques, mais également des composantes motivationnelles, dispositionnelles et contextuelles. Cette structuration reflète la complexité des relations que les étudiants entretiennent avec les environnements numériques d'apprentissage.

Par ailleurs, les résultats montrent que ces compétences varient significativement selon les contextes institutionnels, suggérant que leur développement ne dépend pas uniquement de l'exposition aux technologies, mais également des conditions pédagogiques et des environnements d'apprentissage dans lesquels elles s'inscrivent.

Ainsi, cette deuxième contribution permet de caractériser de manière fine les profils des apprenants et d'introduire un outil de mesure validé, indispensable pour analyser les interactions entre compétences numériques, usages effectifs et apprentissages. Elle constitue le niveau méso du modèle conceptuel, en apportant une compréhension approfondie des ressources individuelles mobilisées dans l'apprentissage de l'anatomie assisté par le numérique.

Article 1: ***“Development and validation of the ICNA scale: a discipline-specific measure of digital competence in anatomy education”***.

Soumis à la revue **Anatomical Sciences Education** le 19 mars 2026

Etat actuel (au 19 juin 2026) : en cours d'évaluation par les relecteurs.

TITLE:

Development and validation of the ICNA scale: a discipline-specific measure of digital competence in anatomy education

AUTHORS :

David Mutombo^{1,2*}, Ninon Puttaert^{3*}, Olivier Prygiel², Allyson Fries², Willy Arung Kalau¹, Aude Lagier², Pierre Bonnet², Valérie Defaweux²

**These authors contributed equally to this work and share first authorship*

¹ Department of Surgery, Faculty of Medicine, University Clinics of Lubumbashi, University of Lubumbashi, Lubumbashi, Democratic Republic of the Congo

² Human Anatomy Laboratory, Department of Biomedical and Preclinical Sciences, Faculty of Medicine, University of Liège, Liège, Belgium

³ Faculty of Psychology, Speech Therapy and Education Sciences - Department of Psychology, University of Liège, Belgium

ABSTRACT**Background**

The digital transformation of health sciences education is profoundly reshaping the ways in which anatomy is learned. The increasing use of three-dimensional models, immersive environments, and interactive digital resources requires students to mobilize specific digital competencies to explore and understand anatomical structures. However, most existing frameworks for assessing digital competence rely on generic approaches and fail to capture the techno-visual and cognitive practices specific to anatomy learning. To date, no validated instrument exists to specifically assess the digital competencies mobilized in this domain

Methods

This study aimed to develop and validate the Anatomy Digital Competence Index (ICNA), an instrument designed to measure students' digital competencies within anatomy learning environments. The questionnaire was administered to 774 students from three higher education institutions in Europe and Africa (University of Liège, Haute Ecole de la Province de Liège, and University of Lubumbashi). The psychometric properties of the scale were examined using exploratory factor analysis (EFA) and confirmatory factor analysis (CFA), internal consistency analyses, and a known-groups approach to compare results across institutional contexts.

Results

Exploratory factor analysis revealed a five-factor structure explaining 51.8% of the total variance, corresponding to different dimensions of students' relationship with digital learning environments: perceived value of digital tools, institutional uses of digital technologies, positivity and academic self-efficacy, perceived digital competence, and critical distance toward

technology. Internal consistency analyses indicated satisfactory reliability across dimensions. Confirmatory factor analysis generally supported the model structure (CFI = 0.89; TLI = 0.88; RMSEA = 0.075; SRMR = 0.079). Comparisons across institutions revealed significant contextual differences, with students from the University of Lubumbashi scoring higher across all dimensions, suggesting that the role and meaning of digital technologies in learning may vary depending on educational environments and access to pedagogical resources. Fit indices close to conventional thresholds are relatively common in early stages of scale development, particularly when constructs are multidimensional and data originate from heterogeneous educational contexts. In such cases, confirmatory factor analysis should be interpreted as a step in progressive structural validation rather than as a definitive test of the model.

Conclusions

The ICNA represents the first instrument specifically designed to assess digital competencies in anatomy learning. The findings support a multidimensional conceptualization of these competencies, integrating technical, motivational, and contextual dimensions. By providing a tool to analyze how students engage with digital learning environments, the ICNA opens new perspectives for research and for the development of pedagogical approaches adapted to the digital transformation of anatomy education.

Keywords

Anatomy education, Digital competence, Scale validation, Medical education, Digital learning environments, Psychometric validation

INTRODUCTION

The development of digital competencies has become a central issue in the training of health professionals. The widespread integration of digital resources—interactive three-dimensional models, immersive environments, hybrid platforms, and artificial intelligence tools—has profoundly transformed teaching modalities, particularly in visually intensive disciplines such as anatomy (García-Robles et al., 2024; Minouei et al., 2024).

In this context, mastering digital environments is no longer a matter of technological convenience; it conditions access to learning resources, the manipulation of complex anatomical representations, and active engagement in multimodal learning systems.

Although several conceptual frameworks have been proposed to structure the assessment of digital competencies, these primarily focus on transversal skills such as information retrieval, digital communication, or content creation.

International frameworks such as DigComp 2.2 (Vuorikari et al., 2022) provide a robust conceptualization of digital competence based on five main domains: information and data literacy, communication and collaboration, digital content creation, safety, and problem solving. Building on this framework, several validated scales have been developed in higher education, including the Students' Digital Competence Scale (SDiCoS; Tzafilkou et al., 2022), the Digital Competence Scale for University Students (DC-US; Wang et al., 2021), and the Digital Literacy Scale (DLS; Amin et al., 2021), as well as various empirically validated adaptations of the

DigComp framework across different cultural contexts (Fan & Wang, 2022; Schwarz et al., 2024; Rodríguez-Miranda et al., 2025; Abubakari et al., 2025).

These instruments generally demonstrate excellent psychometric properties, characterized by stable factorial structures, high internal consistency, and, in some cases, measurement invariance across groups. The CIRANO model (Sawchuk, 2020), widely used to conceptualize digital competencies in academic settings, also provides a robust multidimensional framework integrating technical, informational, and critical dimensions.

However, despite their methodological robustness, these approaches struggle to account for situated digital competencies that emerge within specific disciplinary contexts. They remain largely generic and fail to fully capture the contextualized digital competencies specific to certain disciplines, particularly within the biomedical sciences, as is the case in anatomy.

This limitation is even more critical given that the literature highlights potential biases associated with self-reported measures of digital competence. Several studies have indeed identified phenomena of overestimation or biased perception of competencies among certain student profiles (Davis et al., 2006; Kastorff et al., 2023), thereby reinforcing the need to develop discipline-specific instruments grounded in a rigorous psychometric approach.

In the field of anatomy, learning involves a set of techno-visual practices that extend well beyond the generic digital competencies typically described in existing frameworks. Students are required to dynamically manipulate three-dimensional models, explore serial sections, annotate or segment anatomical structures, interpret multiple representational modalities in an integrated manner (prosections, medical imaging, photogrammetry), and engage in visuospatial reasoning supported by digital tools. The increasing use of immersive technologies, such as virtual and augmented reality, further reinforces the operational and interactive nature of anatomical learning (Langlois et al., 2020; Roach et al., 2020).

In this context, the mismatch between the complexity of digital practices mobilized in anatomy and the currently available measurement instruments highlights a lack of tools capable of capturing these competencies in a contextualized and valid manner.

This lack of contextualized instruments limits the evaluation of current pedagogical approaches and hinders inter-institutional comparisons, particularly across settings with contrasting levels of resources. It also constrains the understanding of the actual impact of immersive digital environments on anatomy learning. To address these limitations, the Anatomy Digital Competence Index (ICNA) was developed as a scale specifically contextualized to anatomy education. Its objective is to provide a simple, standardized, and psychometrically robust tool for reliably measuring self-reported digital competencies in direct relation to contemporary pedagogical practices. The scale also incorporates dimensions that are rarely considered in digital competence instruments, including psychopedagogical variables such as positivity traits and perceived academic self-efficacy, which are known to influence student engagement and academic success. Such an instrument would support pedagogical guidance, facilitate the design of targeted training interventions, and provide a shared framework applicable across diverse institutional contexts at an international level (Car et al., 2025).

The present study aims to validate the Anatomy Digital Competence Index (ICNA) across three contrasting institutions: the University of Liège (Belgium), the Haute École de la Province de Liège (Belgium), and the University of Lubumbashi (Democratic Republic of the Congo). More specifically, it pursues three objectives: (1) to examine the factorial structure and internal consistency of the scale, (2) to assess its construct validity within a psychometric framework, and

(3) to analyze its ability to discriminate between institutional contexts characterized by different technological environments.

By combining a rigorous psychometric methodology with a multicenter approach, this study aims to provide a reliable, contextualized, and transferable instrument to support the assessment and development of digital competencies in anatomy across diverse educational settings at the international level.

MATERIALS AND METHODS

Study design and context

This multicenter cross-sectional study aimed to psychometrically validate the Anatomy Digital Competence Index (ICNA) across three contrasted institutional contexts. Data were collected during the 2024–2025 academic year from students enrolled at the University of Liège (ULiège, Belgium), the Haute École de la Province de Liège (HEPL, Belgium), and the University of Lubumbashi (UNILU, Democratic Republic of the Congo).

These three institutions respectively represent a European academic medical curriculum, a professionally oriented postsecondary program in medical imaging, and a medical curriculum in a resource-constrained context.

This methodological choice aimed to examine the structural robustness of the ICNA across heterogeneous pedagogical and technological environments.

Participants

A total of 774 students participated in the study (UNILU: $n = 368$; ULiège: $n = 373$; HEPL: $n = 33$). Participation was voluntary and anonymous. Questionnaires with missing data preventing the computation of scores were excluded from factor analyses.

Instrument development and adaptation

The Anatomy Digital Competence Index (ICNA) was developed through a structured adaptation of the CIRANO model of academic digital competence. This model, widely used to assess attitudes toward digital technologies, digital literacy, and access to technology, provides a robust theoretical framework validated across various educational and organizational contexts.

However, the CIRANO model remains generic and does not account for the disciplinary specificities of morphological sciences. Anatomy education relies on particular cognitive processes, including the manipulation of three-dimensional representations, multimodal integration of information (imaging, dissection, digital visualization), and the increasing use of immersive environments and artificial intelligence tools.

The development of the ICNA followed a dual approach. On the one hand, the core conceptual structure of the CIRANO model—attitudes toward digital technologies, digital literacy, and

access to equipment—was retained to ensure theoretical continuity and methodological comparability with existing frameworks. On the other hand, substantial adaptations were introduced to contextualize the instrument within the field of anatomy.

These adaptations notably concerned the perceived value of digital tools in understanding anatomical structures, emotional engagement associated with digital tools, and elements related to professional identity construction (projection into the role of a future health professional, perceived competitiveness, positioning as a resource student) (Table 1).

Items were rated on a five-point Likert scale (1 = strongly disagree; 5 = strongly agree). The full version of the questionnaire is provided in the appendix (Additional file 1).

Table 1. Conceptual and disciplinary contributions of the ICNA compared to the CIRANO model

Dimension	CIRANO scale	ICNA (adaptation)	Level of alignment	Discipline-specific added value (Anatomy)
Attitudes toward digital technologies	General attitudes, perceived usefulness, ease of use	Anatomy-contextualized attitudes (understanding of structures, pedagogical usefulness, engagement)	High	Very high
Motivation and emotions	Generic motivation, general interest in digital technologies	Motivation related to digital anatomy (enjoyment, learning atmosphere, boredom, curiosity)	Moderate	High
Digital self-efficacy	Perceived efficacy in using generic digital tools	Self-efficacy applied to anatomy-specific tools (3D models, platforms, imaging)	Moderate	Moderate to high
Digital literacy	Comprehensive assessment of general technical skills	Largely retained, with enrichment (AI, educational platforms)	Very high	Low
Access and equipment	Equipment, frequency, and patterns of use	Dimension preserved with minor adaptations	Very high	None
Professional relevance	Not included in the model	Perceived impact on future medical practice and employability	None	Very high
Disciplinary specificity	Not included in the model	Anchoring in the realities of anatomy education	None	Very high
Identity and social positioning	Not included in the model	Positioning as a resource student, peer recognition	None	Moderate

Language of administration and translation

The questionnaire was administered in French, the language of instruction in all participating institutions. To enable international dissemination, an English version is provided in the appendix of the manuscript (Additional file Annex 1).

The initial translation into English was conducted using a language assistance tool and independently, then revised and harmonized by bilingual members of the research team. An independent back-translation procedure was subsequently performed to verify semantic and conceptual equivalence between the French and English versions. Identified discrepancies were discussed collectively until consensus was reached.

This procedure aligns with methodological recommendations for the cross-cultural adaptation of psychometric instruments (Beaton et al., 2000; World Health Organization, 2016).

Additional variables for construct validity

To examine the construct validity of the ICNA, several complementary variables, distinct from the core dimensions of the instrument, were included in the questionnaire. In line with Messick's (1995) integrative approach to validity, these variables were intended to test the nomological coherence of the scale by examining its expected relationships with theoretically related constructs (convergent validity) or distinct constructs (divergent validity).

The questionnaire also included a set of general sociodemographic questions (Q11–Q17), relating to age, sex, educational background, and parental education level. These descriptive variables were not included in the ICNA score computation but were used to characterize participant profiles.

It should be noted that items related to positivity traits and academic self-efficacy in anatomy (Q1–Q10) were administered only in two of the participating cohorts, namely the University of Lubumbashi and the Haute École de la Province de Liège. These items were not included in the University of Liège cohort. Consequently, analyses involving these dimensions were conducted only on these two subsamples. This difference in administration is related to constraints in the data collection protocol across institutions.

Positivity trait (Q1–Q7)

One variable concerned the positivity trait, measuring a general disposition toward optimism, life satisfaction, and self-confidence. This dimension is based on the French validated Positivity Scale (Boiroux & Junot, 2023), conceptualized as a common factor underlying self-esteem, optimism, and life satisfaction.

This trait, affective and global in nature, is not specific to digital competence. Its inclusion therefore enabled examination of the divergent validity of the ICNA: if the instrument indeed measures contextualized digital competencies, its dimensions should not overlap with a general emotional profile. This distinction is particularly relevant in self-reported measures, where global affective dispositions may bias responses (Davis et al., 2006; Kastorff et al., 2023).

Academic self-efficacy in anatomy (Q8–Q10)

A second variable concerned academic self-efficacy specific to anatomy, defined as the perceived ability to succeed in this learning context. The concept of self-efficacy, derived from Bandura (1997), is a robust predictor of academic performance and engagement.

Within the framework of self-determination theory (Ryan & Deci, 2000), perceived competence is a central determinant of motivation and persistence. It was therefore theoretically relevant to examine potential relationships between perceived digital competence and academic self-efficacy, without including this variable as a structural component of the ICNA.

The objective here was to provide evidence of convergent validity: a moderate correlation would be expected, reflecting a conceptual link between digital ease and academic confidence, without complete redundancy between constructs.

Contextual variables and technological environment (Q55–Q64)

Contextual variables were also collected, including personal digital equipment, patterns of internet use, and connectivity conditions. The literature shows that access to technological resources is a major determinant of the expression of digital competencies and learning opportunities (CIRANO, 2024; Vuorikari et al., 2022).

In contrasted institutional contexts—particularly between European environments and resource-constrained settings—these variables enable examination of the external validity of the instrument. If the ICNA is sensitive to students' actual digital environments, coherent differences should emerge between cohorts with different technological infrastructures.

Data collection procedure

The questionnaires were administered at the beginning of the academic year, prior to the full implementation of digital pedagogical interventions. Data collection was conducted online via a secure institutional platform. Participants received written information and provided informed consent before completing the questionnaire.

Statistical analysis

Statistical analyses were conducted using JAMOV software (version 2.4.12). The suitability of the data for factor analysis was assessed using Bartlett's test of sphericity and the Kaiser–Meyer–Olkin (KMO) index, in accordance with psychometric validation standards.

To support structural validation and limit the risk of capitalization on chance, the total sample was randomly split into two independent subsamples. Items were standardized (z-scores) prior to analyses to ensure comparability and avoid the influence of heterogeneous variance on factor extraction.

An exploratory factor analysis (EFA) was conducted on the first subsample using the minimum residual (minres) method, a robust approach that does not strictly assume multivariate normality. An oblique rotation (oblimin) was selected to allow correlations between factors, consistent with the theoretical assumption of interdependence among dimensions of digital competence in anatomy.

The number of factors was determined based on converging criteria: eigenvalues greater than 1, inspection of the scree plot, and conceptual coherence of the solutions obtained. Factor loadings $\geq .40$ were considered substantial. Items with high cross-loadings or insufficient loadings were examined in light of their theoretical relevance.

The structure identified in the EFA was then tested on the second subsample using confirmatory factor analysis (CFA). Model fit was evaluated using complementary indices: Comparative Fit Index (CFI) and Tucker–Lewis Index (TLI) $\geq .90$ indicating acceptable fit, Root Mean Square Error of Approximation (RMSEA) $\leq .08$, and Standardized Root Mean Square Residual (SRMR) $\leq .08$.

Internal consistency of the identified dimensions was estimated using Cronbach’s α and McDonald’s ω coefficients, the latter being preferred when tau-equivalence among items cannot be assumed.

In addition to factorial validation, inter-context comparisons were conducted to examine external validity. A mean score was calculated for each ICNA dimension. Differences between the three institutional contexts were analyzed using one-way analyses of variance (ANOVA). When significant effects were observed, Tukey post hoc comparisons were performed. To control for inflation of Type I error due to multiple testing, the Benjamini–Hochberg procedure was applied to control the false discovery rate (FDR) (Benjamini & Hochberg, 1995). Effect sizes were estimated using Cohen’s d .

These comparative analyses follow a known-groups validation approach, whereby a valid instrument should be able to distinguish between groups theoretically expected to differ on the measured construct (DeVellis & Thorpe, 2022; Furr, 2018; Messick, 1995).

The three institutional contexts were considered distinct in terms of technological environment and exposure to digital tools. In the absence of a pre-existing validated instrument allowing assessment of convergent or criterion validity, the combination of split-sample factorial validation and known-groups validation constituted a coherent methodological strategy to evaluate both the structural robustness and discriminant capacity of the scale.

Ethical considerations

The study was conducted in accordance with the Declaration of Helsinki and complied with the General Data Protection Regulation (GDPR; EU Regulation 2016/679), as well as national regulations applicable in Belgium and the Democratic Republic of Congo.

A standard information and consent document developed at the University of Liège was adapted to the multicenter context. Participation was voluntary and anonymous. All participants received written information about the study objectives, procedures, and data processing prior to participation, and informed consent was obtained electronically.

Participants were informed of their rights regarding access, rectification, and withdrawal of consent, and could exercise these rights through designated institutional contact points at the University of Liège and the University of Lubumbashi.

RESULTS

Sample description

The final sample included 774 students from three higher education institutions representing contrasted pedagogical contexts. The University of Liège (ULiège, Belgium) cohort consisted of 373 first-year medical students. The University of Lubumbashi (UNILU, Democratic Republic of the Congo) cohort included 368 second-year medical students. Finally, the Haute École de la Province de Liège (HEPL, Belgium) comprised 33 students enrolled in a professionally oriented medical imaging program.

Data collection was conducted during the 2024–2025 academic year. Participation was voluntary and anonymous. Inclusion criteria were enrollment in one of the targeted programs and provision of informed consent. Incomplete questionnaires that did not allow reliable score computation were excluded from factor analyses, in accordance with the protocol described in the Methods section.

The distribution of sample sizes reflects the respective institutional sizes of the programs involved. The two university cohorts (ULiège and UNILU) present comparable sample sizes, whereas the HEPL cohort is smaller, which is considered in the interpretation of subsequent analyses.

Descriptive analysis of the scale

Descriptive statistics for all questionnaire items are presented in Table 2, including means, standard deviations, interquartile ranges, and full response distributions across the five-point Likert scale.

It should be noted that items Q1 to Q10—relating to positivity traits (Q1–Q7) and academic self-efficacy in anatomy (Q8–Q10)—were administered only to the UNILU and HEPL cohorts ($N \approx 401$). The remaining items (Q18–Q54) were completed by all participants ($N = 774$), which explains differences in sample sizes observed in the descriptive statistics.

For the positivity-related items (Q1–Q10), mean scores ranged from 3.39 to 4.54. Response distributions were strongly skewed toward the upper categories of the Likert scale, with a majority of responses concentrated in categories 4 and 5 across most items (typically exceeding 50%–60%). Lower categories (1 and 2) were marginal, generally representing less than 5%–10% of responses. This pattern reflects a high level of agreement and a generally positive self-perception among respondents.

For the ICNA-related items (Q18–Q54), mean scores ranged from 1.70 to 3.89, indicating greater variability in responses. In contrast to Q1–Q10, response distributions were more heterogeneous, with a broader spread across all five categories. Standard deviations (1.30–1.56) and interquartile ranges (mostly between 1 and 2) further support this greater dispersion.

Item-level frequency patterns revealed meaningful differences in response profiles. Some items (e.g., Q22, Q31) showed a clear concentration in the lower categories, with more than 50% of responses in categories 1 and 2, indicating disagreement or low endorsement. Conversely, other items (e.g., Q24, Q33, Q43) were characterized by a higher proportion of responses in the upper categories (4 and 5), often exceeding 70%, reflecting strong agreement.

Overall, response distributions varied substantially across items, capturing differences in central tendency, dispersion, and endorsement patterns. Importantly, all response categories (1–5) were represented across the dataset, indicating the absence of floor or ceiling effects and supporting the adequacy of the data for subsequent exploratory factor analysis.

Table 2: Descriptive Statistics for ICNA Items

Item	N	Missing	Mean	SD	IQR	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)
Q1	401	546	4.4339	0.9855	1.00	2.49	1.25	7.48	22.94	64.84
Q2	401	546	3.8978	1.2637	2.00	6.48	7.73	13.22	29.68	41.90
Q3	401	546	4.4489	0.9450	1.00	2.24	1.25	4.99	27.43	63.09
Q4	401	546	4.1222	1.1281	1.00	3.74	5.74	8.48	33.67	47.38
Q5	401	546	3.3865	1.4535	3.00	15.46	10.22	16.46	28.43	27.93
Q6	401	546	4.2419	1.0903	1.00	2.99	3.24	12.47	24.19	56.11
Q7	401	546	4.4364	1.0376	1.00	2.00	3.99	4.99	20.20	67.58
Q8	401	546	4.4439	0.9233	1.00	1.00	1.50	4.74	30.18	61.10
Q9	401	546	4.5411	0.8740	1.00	1.25	0.00	3.24	26.93	67.08
Q10	401	546	4.4314	0.9412	1.00	1.25	1.00	3.99	32.17	59.85
Q18	774	173	3.8217	1.3778	2.00	1.29	3.23	14.21	37.73	36.18
Q19	774	173	3.7584	1.3874	2.00	1.16	3.23	13.05	43.02	31.40
Q20	774	173	3.8463	1.4666	2.00	1.16	5.04	12.79	29.33	43.54
Q21	774	173	3.5426	1.4531	2.00	4.65	5.69	16.28	38.76	26.87
Q22	774	173	1.9935	1.3033	2.00	34.88	28.30	14.73	8.01	6.33
Q23	774	173	3.2584	1.4343	1.00	6.33	9.69	24.03	33.59	18.73
Q24	774	173	3.8863	1.3912	1.00	1.29	3.36	8.92	40.18	38.63
Q25	774	173	3.7946	1.4144	2.00	1.42	4.01	12.92	37.60	36.18
Q26	774	173	3.2791	1.4511	1.00	4.65	12.40	24.55	28.42	22.22
Q27	774	173	3.8463	1.3680	1.00	1.03	1.55	12.66	41.86	35.01
Q28	774	173	3.7222	1.4166	2.00	1.55	4.91	15.12	37.21	33.33
Q29	774	173	3.4044	1.5100	2.00	5.56	9.95	19.38	29.33	27.91
Q30	774	173	3.2674	1.5096	2.00	6.46	13.05	20.54	27.78	24.29
Q31	774	173	1.7041	1.1968	1.00	46.77	25.45	10.21	4.39	4.91
Q32	774	173	3.6124	1.3994	2.00	1.81	4.91	17.70	40.70	26.74
Q33	774	173	3.8863	1.4261	1.00	1.68	3.75	6.46	40.44	39.66
Q34	774	173	3.1873	1.4547	2.00	5.81	14.47	19.64	34.63	17.31
Q35	774	173	2.4522	1.4802	3.00	25.07	18.22	20.16	18.86	9.56
Q36	774	173	2.7739	1.5044	2.00	16.54	17.31	18.22	28.04	11.89
Q37	774	173	2.8514	1.5587	2.75	16.54	12.79	21.84	24.03	16.28
Q38	774	173	3.4703	1.4578	1.00	4.39	6.98	17.96	37.86	24.68
Q39	774	173	3.2196	1.4754	2.00	6.85	10.08	21.58	34.63	18.35
Q40	774	173	3.4845	1.4853	2.00	5.17	6.33	15.25	39.41	25.45
Q41	774	173	3.7881	1.5137	2.00	2.84	5.17	9.43	32.82	41.21
Q42	774	173	2.7700	1.4562	2.00	12.53	19.90	24.16	22.87	12.15
Q43	774	173	3.8643	1.5084	1.00	3.10	3.75	7.49	32.95	44.32
Q44	774	173	3.6047	1.4659	2.00	3.10	6.07	15.38	36.82	30.36
Q45	774	173	3.0956	1.4247	2.00	6.33	13.82	24.03	33.59	13.82

Q46	774	173	3.7158	1.4412	2.00	1.81	3.88	12.92	40.44	32.30
Q47	774	173	3.0659	1.4793	2.00	7.75	15.63	22.22	29.07	16.93
Q48	774	173	3.0116	1.4337	2.00	7.49	15.50	25.45	29.46	13.70
Q49	774	173	3.2752	1.4153	1.00	4.13	12.27	18.22	41.34	15.76
Q50	774	173	3.1266	1.3984	2.00	5.17	13.31	24.55	35.66	12.92
Q51	774	173	3.5349	1.4363	1.00	2.97	6.46	15.89	41.47	24.81
Q52	774	173	3.2196	1.5280	2.00	7.75	13.70	17.05	31.14	22.22
Q53	774	173	2.8863	1.4495	2.00	10.08	18.61	23.64	26.62	12.79
Q54	774	173	3.5568	1.3832	1.00	2.33	4.65	18.22	43.93	22.74

Note. All items were rated on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). *M* = mean; *SD* = standard deviation; *IQR* = interquartile range. Percentages represent the distribution of responses across categories.

Suitability of the data for factor analysis

The suitability of the data for exploratory factor analysis was assessed for the combined sample as well as for each cohort separately. Bartlett's tests of sphericity were significant in all three contexts ($p < .001$), indicating that correlation matrices were not identity matrices.

Kaiser–Meyer–Olkin (KMO) indices were satisfactory for UNILU and ULiège, while the KMO value observed for the HEPL cohort reached the minimum acceptable threshold ($KMO \approx 0.50$), suggesting cautious interpretation of results for this smaller subsample.

Exploratory factor analysis

An exploratory factor analysis (EFA) was conducted on the randomly split subsample ($N = 474$), standardized into z-scores, using minimum residual (minres) extraction and oblique rotation (oblimin), allowing for correlations between factors.

The number of factors was determined based on eigenvalues greater than 1, inspection of the scree plot, and conceptual coherence of the solutions. These criteria converged toward a five-factor solution.

The five-factor solution explained 51.88% of the total variance (Table 4). The respective contributions were: Factor 1 = 12.52%, Factor 2 = 11.57%, Factor 3 = 11.48%, Factor 4 = 10.82%, and Factor 5 = 5.48%.

Factor loadings are presented in Table 3, grouped by dominant factor. The majority of items showed substantial primary loadings, with some moderate cross-loadings (e.g., Q9, Q10, Q33, Q41, Q46, and Q52), consistent with an oblique structure and partial interdependence between dimensions.

Table 3: Exploratory Factor Analysis (Minimum Residual Extraction, Oblimin Rotation): Factor Loadings ($\geq .40$), All Cohorts Combined, All Items Grouped by Dominant Factor

Item	F1	F2	F3	F4	F5	Uniqueness
Factor 1						
Q25	.661					.410
Q28	.644					.345
Q20	.615					.575
Q18	.596					.367
Q27	.551					.407
Q24	.516					.420
Q33	.511					.437
Q29	.452					.460
Q46	.430			.416*		.458
Q32	.416					.523
Q19	.416					.599
Factor 2						
Q39		.811				.294
Q35		.791				.267
Q38		.694				.362
Q42		.661				.302
Q36		.602				.395
Q37		.509				.576
Q34		.472				.401
Factor 3						
Q7			.689			.364
Q1			.650			.437
Q3			.641			.446
Q6			.625			.455
Q4			.617			.501
Q9			.598			.289
Q8			.526			.410
Q2			.482			.638
Q10			.451			.414
Factor 4						
Q49				.806		.347
Q50				.682		.392
Q47				.644		.336
Q45				.621		.467
Q48				.601		.463
Q52				.485		.513
Q51				.398*		.506
Factor 5						
Q23					.573	.673
Q31					.558	.648
Q22					.552	.660
Q5					.457	.797
Q43				.357*	.395*	.556
Q41					.354	.621
Q44					.345	.582

Note. Extraction method: minimum residual (minres). Rotation method: oblimin. Only factor loadings $\geq .40$ are displayed. Cross-loadings are indicated with an asterisk. Uniqueness values represent the proportion of variance not explained by the retained factors.

Table 4: Variance Explained by the Five-Factor Solution (Minimum Residual Extraction)

Factor	SS Loadings	% of Variance	Cumulative %
1	5.89	12.52	12.52
2	5.44	11.57	24.09
3	5.40	11.48	35.57
4	5.08	10.82	46.39
5	2.58	5.48	51.88

Note. Extraction method: minimum residual (minres). Percentages are rounded to two decimal places.

Inter-factor correlations ranged from .26 to .50 (Table 5). The strongest associations were observed between Factors 1, 2, and 3 ($r \approx .406-.480$), whereas Factor 5 appeared more distinct, with weaker correlations with other dimensions ($r = .26$ to $.307$). Overall, these results support a multidimensional structure composed of differentiated but moderately interconnected factors.

Table 5: Inter-Factor Correlations (Oblimin Rotation)

Factor	1	2	3	4	5
1	—	.406	.480	.339	.260
2		—	.459	.501	.307
3			—	.452	.275
4				—	.291
5					—

Note. Values represent correlations between latent factors following oblimin rotation. Coefficients are rounded to three decimal places.

Conceptual interpretation of factors and instrument finalization

Beyond the statistical identification of a five-factor solution, an in-depth conceptual interpretation was conducted to ensure alignment between the empirical structure and the initial theoretical framework of the ICNA (Additional file Annex 2). A detailed examination of item content within each factor enabled the identification of coherent clusters corresponding to the conceptual dimensions anticipated during instrument development.

The first factor (**motivational value of digital technologies in anatomy**) primarily includes items related to the perceived value of digital tools in anatomy learning, including usefulness for understanding structures, engagement, perceived modernity, future professional competitiveness, and interest in discipline-specific digital tools. This dimension reflects the importance attributed to digital technologies in the academic and professional trajectory.

The second factor (**institutional uses of digital technologies**) includes items related to institutional digital environments and formal tools for organization and collaboration (collaborative platforms, intranet, document management systems, project management tools). It reflects a structural and organizational dimension of digital literacy.

The third factor (**positivity and academic self-efficacy**) combines items from the general positivity scale (optimism, self-confidence, life satisfaction) with items measuring academic self-

efficacy in anatomy. This empirical convergence suggests the existence of a common psychosocial core linking general positive disposition and perceived academic competence.

The fourth factor (**perceived digital competence**) corresponds to general perceived digital competencies, including technical problem-solving, mastery of digital tools, online information retrieval, and awareness of digital-related issues (cybersecurity, plagiarism).

Finally, the fifth factor (**critical distance and ambivalence toward digital technologies**) groups items reflecting reservation or ambivalence toward digital technologies, including attitudes of rejection, perceptions of time loss, and certain social or peripheral uses of digital tools.

Factor naming was based on a combined analysis of dominant factor loadings, semantic coherence of items, and alignment with the initial theoretical model. This approach ensured a conceptually grounded interpretation rather than a purely statistical reading.

Final item selection did not rely solely on psychometric criteria (low loadings, substantial cross-loadings, high uniqueness) but also incorporated qualitative evaluation of conceptual relevance. In accordance with recommendations for psychometric instrument development, theoretical relevance was considered to avoid the removal of meaningful items based solely on statistical criteria.

Based on these combined criteria—factorial robustness, internal consistency, and conceptual coherence—ten items were removed. Thus, from the initial 47 items, 37 were retained for subsequent analyses. The detailed list of removed items is provided in Appendix (Additional file Annex 3).

Internal consistency

Cronbach's α and McDonald's ω coefficients were calculated for each dimension, ranging from [.60; .97] and [.62; .97], respectively, indicating satisfactory internal consistency across factors (Table 6).

Table 6: Internal Consistency and Descriptive Statistics of the Five-Factor Solution

Factor	Cronbach's α	McDonald's ω	M	SD
1	.966	.967	3.76	1.23
2	.935	.935	2.99	1.26
3	.903	.911	4.33	0.75
4	.932	.933	3.13	1.25
5	.602	.620	2.71	0.91

Note. α = Cronbach's alpha; ω = McDonald's omega; M = mean; SD = standard deviation. Coefficients are based on the retained factor structure.

Confirmatory factor analysis

Confirmatory factor analysis was conducted on the second half of the sample ($n = 473$), testing the five-factor model suggested by the EFA. The model yielded a significant $\chi^2(619) = 1931.7$, $p < .001$, which is expected given the large sample size.

Fit indices were as follows: $\chi^2/df = 3.12$, CFI = 0.89, TLI = 0.88, SRMR = 0.079, and RMSEA = 0.075 (90% CI [0.071; 0.079]).

External validation – known-groups

In line with the known-groups validation approach, we hypothesized that the three institutional contexts would differ significantly across the dimensions measured by the ICNA, due to differences in levels of digital exposure, technological environments, and pedagogical dynamics.

More specifically, the UNILU context, characterized by a more recent and potentially more salient digital transformation, may lead to more pronounced perceptions of digital technologies. In contrast, the Belgian contexts (ULiège and HEPL), which are more technologically established, may exhibit more moderate and homogeneous profiles.

One-way analyses of variance (ANOVA) were conducted to examine differences between the three institutional contexts (Table 7). Significant differences were observed across all five factors: Factor 1, $F = 97.86$, $p < .001$; Factor 2, $F = 150.09$, $p < .001$; Factor 3, $F = 106.35$, $p < .001$; Factor 4, $F = 27.10$, $p < .001$; and Factor 5, $F = 7.39$, $p = .007$.

Descriptively, students from UNILU consistently showed higher mean scores than those from the two Belgian institutions. In contrast, HEPL and ULiège displayed broadly comparable profiles across available dimensions.

Post hoc comparisons using Tukey correction confirmed this pattern. No significant differences were observed between HEPL and ULiège for Factors 1, 2, and 4 (all $p > .20$), with small effect sizes ($d \leq 0.30$). In contrast, significant differences were consistently found between UNILU and each Belgian institution, with effect sizes ranging from moderate to large ($0.49 \leq d \leq 1.27$), and a particularly strong effect for Factor 3 in the HEPL–UNILU comparison ($d = 1.87$).

Comparisons involving Factors 3 and 5 could not be performed for ULiège due to missing data for these dimensions.

Overall, these findings support the discriminant capacity of the ICNA across distinct institutional contexts, providing evidence for its external validity through a known-groups approach.

Table 7: Comparison of the Three Programs Across the Five Factors (ANOVA Results)

Dimension	HEPL (n = 33)		ULiège (n = 373)		UNILU (n = 368)		F	p
	M	SD	M	SD	M	SD		
Factor 1	3.23	1.47	3.22	1.40	4.34	0.61	97.86	< .001
Factor 2	2.58	1.28	2.26	1.18	3.63	0.94	150.09	< .001
Factor 3	3.14	1.21	—	—	4.44	0.63	106.35	< .001
Factor 4	2.70	1.36	2.84	1.42	3.47	0.93	27.10	< .001
Factor 5	2.33	1.06	—	—	2.77	0.88	7.39	.007

Note. Values are presented as mean (M) and standard deviation (SD). F values derive from one-way ANOVA comparing the three institutional contexts.

Table 8: Post Hoc Comparisons Between Programs (Tukey-Adjusted p Values and Effect Sizes)

Dimension	HEPL – ULiège		HEPL – UNILU		ULiège – UNILU	
	p (Tukey)	Cohen's d	p (Tukey)	Cohen's d	p (Tukey)	Cohen's d
Factor 1	.86	0.09	< .001	0.92	< .001	1.01
Factor 2	.23	0.30	< .001	0.97	< .001	1.27
Factor 3	—	—	< .001	1.87	—	—
Factor 4	.80	0.12	.002	0.63	< .001	0.52
Factor 5	—	—	.007	0.49	—	—

Note : Post hoc pairwise comparisons were conducted using Tukey's honestly significant difference (HSD) correction to adjust for multiple testing. Effect sizes are reported as Cohen's d. Dashes indicate that comparisons were not applicable due to missing data for one of the programs.

DISCUSSION

The present study aimed to develop and validate the Anatomy Digital Competence Index (ICNA), a scale designed to measure digital competencies within the specific context of anatomy learning. The results support the relevance of a multidimensional approach to these competencies and suggest that the instrument is sensitive to the contextual dynamics of digital learning environments.

Three main findings warrant discussion: (1) the factorial structure of the scale and the dimensions it highlights, (2) the sensitivity of the instrument to the contrasted institutional contexts in which it was tested, and (3) the methodological implications related to the validation of a discipline-specific instrument in heterogeneous educational environments.

Interpretation of the factorial structure

First, the factorial structure obtained suggests that the digital competencies mobilized in anatomy learning are not limited to technical skills, but are organized around cognitive, motivational, and dispositional dimensions. The five factors identified by the ICNA thus reflect

different facets of the relationship students maintain with digital learning environments: the perceived value and usefulness of digital tools in anatomy learning, institutional uses of digital platforms and resources, the sense of personal digital competence, positive dispositions associated with academic engagement, as well as a form of critical distance toward technologies.

This multidimensional structuring suggests that the digital competencies mobilized in anatomy are embedded within broader learning processes, in which the use of technologies is closely linked to students' cognitive engagement and their pedagogical experience.

The findings of this study are consistent with a growing body of literature showing that anatomy learning involves complex interactions between technical skills, cognitive processes, and student engagement in digital environments. Three-dimensional and immersive technologies, such as virtual and augmented reality, have indeed transformed the way students explore and manipulate anatomical structures, fostering spatial interaction and active learning (Langlois et al., 2020; Moro et al., 2017; Roach et al., 2021).

In this context, the identification of distinct dimensions related to digital competence, motivational dispositions, and institutional uses of digital technologies appears consistent with recent developments in anatomy learning environments, which are increasingly characterized by the integration of interactive digital tools.

This five-dimensional structure shows several convergences with existing conceptual models of digital competence (Table 9). Dimensions related to technical competence and institutional uses align with digital literacy frameworks and DigComp (Ferrari, 2013; Vuorikari et al., 2022; Ng, 2012). Furthermore, the inclusion of dispositional dimensions such as perceived value of digital tools and personal self-efficacy is consistent with research on engagement and technology acceptance in educational contexts (Bandura, 1997; Hatlevik et al., 2015). Finally, the presence of a critical distance dimension reflects the growing importance of reflective attitudes in contemporary conceptualizations of digital competence (Janssen et al., 2013).

These convergences suggest that the ICNA does not merely measure isolated technical skills but captures a broader configuration of competencies and dispositions that structure students' engagement in digital learning environments.

From this perspective, the findings of the present study suggest that digital competencies mobilized in anatomy learning are part of a multidimensional dynamic integrating technical, dispositional, and contextual dimensions.

Table 9. Correspondence between ICNA dimensions and theoretical frameworks in digital competence literature

ICNA Factor	What it measures	Corresponding literature	Contribution
F1 – Motivational value of digital technologies	Perceived usefulness of digital tools for learning anatomy	Technology Acceptance Model (Davis, 1989); academic motivation (Eccles & Wigfield, 2002)	Shows that adoption of digital tools depends on perceived value for learning
F2 – Institutional uses of digital technologies	Interaction with academic digital platforms and resources	DigComp (Ferrari, 2013; Vuorikari et al., 2022)	Corresponds to “information,” “communication,” and “problem-solving” dimensions

F3 – Positivity / personal self-efficacy	Sense of competence and positive disposition toward digital tools	Self-efficacy (Bandura, 1997); digital self-efficacy (Hatlevik et al., 2015)	Explains students' engagement in digital environments
F4 – Perceived digital competence	Technical ability to use digital tools	Digital literacy (Ng, 2012); DigComp technical skills	Classical dimension of digital competence instruments
F5 – Critical distance toward digital technologies	Reflective and critical stance toward technologies	Digital critical literacy (Janssen et al., 2013; Ng, 2012)	Rarely measured but essential for mature digital competence

Interpretation of inter-context differences

Beyond the internal structure of the scale, comparative analyses across institutional contexts provide particularly insightful perspectives on how these dimensions are expressed in contrasting educational environments. The results show that students from the University of Lubumbashi obtained higher scores across all ICNA dimensions. This consistent pattern suggests that the role and meaning of digital technologies in learning may vary significantly depending on institutional contexts and access to educational resources.

In environments where educational resources are more limited, digital technologies may be perceived as particularly structuring tools for learning. The findings observed in Lubumbashi suggest that digital technologies may function as a key lever for access to knowledge, enabling students to explore complex anatomical representations and access learning resources that are otherwise difficult to obtain. In this context, digital tools do not merely represent one pedagogical support among others but may be perceived as a major academic opportunity capable of transforming students' learning experience. This interpretation is consistent with research on digital inequalities, which shows that the benefits associated with technologies depend not only on access to tools, but also on appropriation conditions, competencies, and the educational resources available within institutional contexts (van Dijk, 2020; Warschauer, 2004). In health education, several studies have also highlighted that educational technologies can play a structuring role in resource-constrained settings by facilitating access to learning content and partially compensating for material or organizational constraints (Barteit et al., 2019; Frehywot et al., 2013).

This interpretation is further reinforced by the observation that differences between contexts concern not only dimensions related to digital usage or technical competence, but also the dispositional dimensions of the scale. In particular, the factor related to positivity and personal self-efficacy shows a particularly strong effect across institutions. This finding suggests that the use of digital technologies may also be associated with an increased sense of academic competence and a stronger projection into academic trajectories. From this perspective, digital technologies appear not only as cognitive tools facilitating learning, but also as potential supports for the development of self-efficacy within the academic pathway. This observation aligns with research showing that digital competence and engagement in technology-mediated learning environments are closely linked to dispositional factors such as confidence in tool use and perceived self-efficacy (Hatlevik et al., 2015).

Conversely, in contexts where digital learning environments are already widely integrated into pedagogical practices, as is the case in the European institutions studied, digital technologies may be perceived as more ordinary components of the educational landscape. This

normalization of digital tools may contribute to reducing the perceived added value attributed to these technologies by students, which could explain the more moderate scores observed in these contexts. As highlighted by Selwyn (2022), the integration of digital technologies in education occurs within complex sociotechnical dynamics in which technologies gradually become normalized as they are fully embedded in institutional practices.

From this perspective, the results of the present study suggest that the ICNA does not solely capture technical digital competencies, but also broader dimensions related to how students position themselves toward digital learning environments. The instrument thus appears sensitive to contextual dynamics of access to educational resources and to the meanings attributed to digital technologies across institutional settings.

These findings can be interpreted through a multilevel perspective of digital learning environments. At a macro level, the differences observed between institutions likely reflect contrasted educational and technological contexts. At a meso level, these dynamics are embedded within institutional characteristics of pedagogical environments and the digital infrastructures available to students. Finally, at a micro level, the differences observed are reflected in students' individual dispositions toward technologies and their engagement in digital learning environments. This multilevel perspective aligns with contemporary conceptualizations of digital inequalities, which distinguish between access to technologies, digital skills and uses, and the educational outcomes derived from them (Scheerder et al., 2017; van Dijk, 2020).

However, these findings should be interpreted with caution. Differences observed between institutions may also reflect other contextual factors, such as variations in local pedagogical practices, students' academic trajectories, or cultural differences in the perception and self-assessment of digital competence. As emphasized in the literature, the effects of digital technologies on learning strongly depend on the social and institutional contexts in which they are embedded (Selwyn, 2022; van Dijk, 2020). Therefore, the results should be understood as indicating possible contextual dynamics rather than a direct causal relationship between technological environments and student dispositions.

This multilevel interpretation is summarized in the conceptual model presented in Figure 1.

Multilevel model of digital competencies in anatomy learning

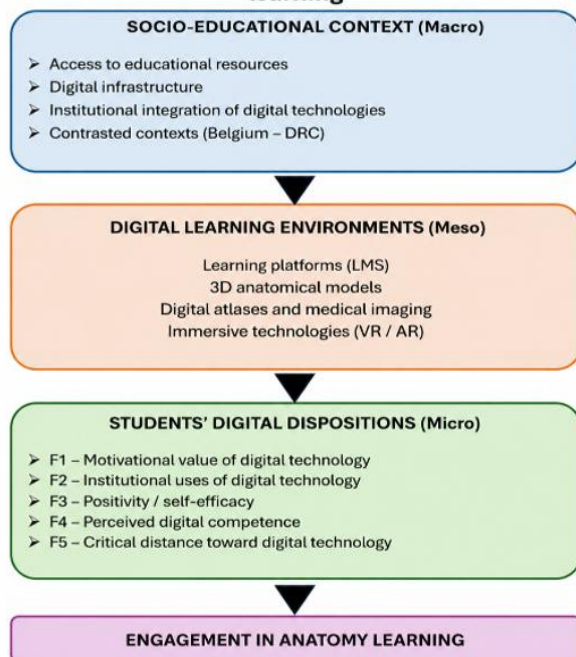


Figure 1. Multilevel conceptual model of digital competencies in anatomy learning. This model illustrates how digital competencies mobilized in anatomy learning emerge from the interaction between three levels: the socio-educational context (macro level), the digital learning environments implemented within institutions (meso level), and students' individual dispositions toward digital technologies (micro level), as measured by the ICNA scale. These interacting dimensions shape students' engagement in digitally mediated anatomy learning.

Psychometric robustness and validity of the instrument

The findings of this study overall support the psychometric robustness of the ICNA and confirm the relevance of a multidimensional structure of digital competencies in the context of anatomy learning. The exploratory factor analysis identified a five-dimensional organization that is conceptually coherent and reflects different facets of students' relationships with digital learning environments. This multidimensional structure is consistent with methodological recommendations in psychometric instrument development, which emphasize the importance of exploratory factor analysis in identifying latent constructs prior to confirmatory testing (DeVellis & Thorpe, 2022; Furr, 2018).

Internal consistency across the different dimensions was satisfactory, indicating good homogeneity of items within each factor. These results suggest that the identified dimensions capture relatively distinct constructs while remaining conceptually related, consistent with an oblique structure of digital competencies in anatomy learning (Taber, 2018).

The confirmatory factor analysis tested the structure identified in the exploratory phase. Model fit for the five-factor solution was moderate (CFI = 0.89; TLI = 0.88; SRMR = 0.079; RMSEA = 0.075). Such fit indices are not uncommon in early stages of scale development, particularly when constructs are multidimensional and data are collected across heterogeneous educational contexts (Brown, 2015; Kline, 2016).

In such contexts, confirmatory factor analysis should be interpreted as part of a process of progressive structural validation rather than as a definitive test of the model.

First, the multicentric nature of the sample implies potentially highly heterogeneous pedagogical and technological contexts, which may affect measurement equivalence across groups. Second, the partial administration of certain item blocks in one cohort—due to study design constraints—resulted in missing data that may have reduced the stability of the covariance matrices. Finally, the oblique structure identified in the exploratory factor analysis included moderate cross-loadings between some factors, whereas confirmatory factor analysis imposes a simple structure in which cross-loadings are constrained to zero. In such situations, it is common for the fit of the confirmatory model to appear more conservative than that suggested by the exploratory analysis.

Thus, these results should be considered as an initial step in establishing structural validity. Future research could extend this work by testing measurement invariance across contexts and by using more flexible approaches such as Exploratory Structural Equation Modeling (ESEM), which allows the modeling of cross-loadings within a confirmatory framework (Marsh et al., 2014).

In such contexts, confirmatory factor analysis should be interpreted as part of a process of progressive structural validation rather than as a definitive test of the model.

From this perspective, the findings should be considered as an initial step in establishing the structural validity of the instrument. Future research could usefully extend these analyses by examining measurement invariance across institutional contexts and by mobilizing more integrative methodological approaches, such as Exploratory Structural Equation Modeling (ESEM), which allows for the modeling of moderate cross-loadings while retaining a confirmatory framework (Marsh et al., 2014).

Beyond structural validation, the present study also explored the external validity of the instrument through a known-groups approach. Comparisons conducted across the three institutional contexts showed that the ICNA was able to discriminate between profiles of students evolving in different pedagogical and technological environments. This ability to discriminate across institutional contexts provides additional support for the external validity of the instrument, suggesting that the ICNA is sensitive to structural differences in digital learning environments. Such discriminative capacity constitutes an important element of external validity, particularly in situations where no pre-existing validated instrument allows for the direct assessment of the same construct. In the field of educational measurement, the so-called known-groups approach is frequently used to provide evidence of validity when groups are theoretically expected to differ on the construct being measured (Messick, 1995; DeVellis & Thorpe, 2022).

From this perspective, the ICNA appears not only as a tool for measuring self-reported digital competencies in anatomy learning, but also as a potentially useful instrument for identifying student profiles with differentiated support needs in the use of digital learning environments. By proposing an approach specifically designed to address the unique demands of anatomy, the ICNA constitutes an original and innovative tool that fills a major methodological gap in the field. Such applications could contribute to more precisely informing pedagogical design and student support strategies in educational contexts increasingly shaped by digital technologies.

Limitations and future directions

Several limitations should be considered when interpreting the findings of this study. First, the instrument relies on self-reported measures of students' digital competencies. Although this type of approach is commonly used in the assessment of digital competence, it may be influenced by perception biases or social desirability bias, with some students potentially overestimating or underestimating their actual competencies. Future research could usefully complement these measures with more objective indicators of digital performance or through the analysis of learning traces within digital environments.

Second, although the study was conducted across multiple institutions, the size and composition of the sample remain specific to the contexts examined. Furthermore, the relatively small size of certain subsamples, particularly in one of the institutional contexts, calls for cautious interpretation of the findings and highlights the need for further validation studies in larger and more diverse samples. As with any factor analysis, the observed structure may be partially dependent on sample characteristics.

Third, the study did not include an external validated instrument allowing for the direct assessment of the scale's convergent validity. In this context, the validation strategy relied on a combination of factor analyses and comparisons between contrasted groups. Although this approach is recognized in the psychometric literature when no directly comparable reference instrument is available (Messick, 1995; DeVellis & Thorpe, 2022), future research could strengthen validity evidence by examining the relationships between ICNA scores and other indicators of student engagement or academic performance.

Finally, the analyses conducted in this study did not allow for a formal examination of measurement invariance across the different institutional contexts. Given that the instrument is intended for use in diverse educational settings, the assessment of such invariance constitutes an important step for future research. Additional studies could therefore investigate measurement invariance of the scale across institutions, programs, or different cultural contexts.

Despite these limitations, the study makes several important contributions. It proposes the first scales specifically contextualized to assess digital competencies in anatomy learning and highlights the multidimensional nature of these competencies. The findings also suggest that these competencies cannot be understood independently of the pedagogical and institutional contexts in which they develop. By combining psychometric validation with a comparative approach across contrasted educational contexts, this study opens perspectives for a broader use of the ICNA in the analysis of digital learning environments in anatomy and, more broadly, in health education.

CONCLUSION

This study aimed to develop and validate the Anatomy Digital Competence Index (ICNA), an instrument designed to measure students' digital competencies within the specific context of anatomy learning. The findings provide initial robust evidence of psychometric validity and support the relevance of a multidimensional approach to digital competencies in technology-mediated learning environments.

The identified factorial structure highlights five complementary dimensions—motivational value of digital technologies, institutional uses of digital environments, perceived personal competence, positive dispositions toward technologies, and critical distance toward digital tools—which reflect different facets of the relationship students maintain with the digital resources mobilized in their training. These findings suggest that digital competencies mobilized in anatomy learning cannot be reduced to mere technical proficiency, but are embedded within a broader set of cognitive, motivational, and contextual processes.

Comparisons across institutional contexts further show that these competencies are expressed differently depending on the socio-educational environments in which students evolve. This observation underscores that the role and meaning of digital technologies in learning depend not only on the availability of technological tools, but also on the pedagogical and institutional contexts in which they are embedded.

From this perspective, the ICNA appears not only as an instrument for measuring self-reported digital competencies, but also as a tool for exploring the educational dynamics that structure digital learning environments in anatomy.

More broadly, this study suggests that understanding students' digital competencies constitutes a key dimension for analyzing the contemporary evolution of anatomy education, at the intersection of technological, pedagogical, and institutional transformations that are currently shaping health professions education.

REFERENCES

- Abubakari, M. S., Zakaria, G. A. N., & Musa, J. (2025). Validating the DigComp framework among university students across different educational systems. *Discover Education*, 4, 200. <https://doi.org/10.1007/s44217-025-00652-x>
- Amin, H., Malik, M. A., & Akkaya, B. (2021). Development and validation of digital literacy scale (DLS) and its implication for higher education. *International Journal of Distance Education and E-Learning*, 7(1), 24–45. <https://doi.org/10.36261/ijdeel.v7i1.2224>
- Baek, S. W., Yeo, T., Lee, H. J., Moon, Y. J., Kim, Y. H., Park, C., Jung, J., Huh, Y., Chin, S. O., Kim, J., & Kim, D. (2024). Systematic analysis of anatomy virtual reality (VR) apps for advanced education and further applications. *Scientific Reports*, 14, 31835. <https://doi.org/10.1038/s41598-024-82945-z>
- Bandura, A. (1997). *Self-efficacy: The exercise of control*. W.H. Freeman. **ISBN :978-0716728504**
- Barteit, S., Guzek, D., Jahn, A., Bärnighausen, T., Bowa, A., & Rockers, P. C. (2019). Evaluation of e-learning for medical education in low- and middle-income countries: A systematic review. *Computers & Education*, 145, 103726. <https://doi.org/10.1016/j.compedu.2019.103726>
- Beaton, D. E., Bombardier, C., Guillemin, F., & Ferraz, M. B. (2000). Guidelines for the process of cross-cultural adaptation of self-report measures. *Spine*, 25(24), 3186–3191. <https://doi.org/10.1097/00007632-200012150-00014>
- Boiroux, F., & Junot, A. (2023). La version française de l'échelle de positivité : Évaluer le facteur commun entre l'estime de soi, l'optimisme et la satisfaction de vie. *Psychologie Française*, 68(2), 191–207. <https://doi.org/10.1016/j.psfr.2021.10.005>
- Boujut, É., & Bruchon-Schweitzer, M. (2007). Rôle de certains facteurs psychosociaux dans la réussite universitaire d'étudiants de première année. *L'Orientation Scolaire et Professionnelle*, 36(2). <https://doi.org/10.4000/osp.1367>
- Brown, T. A. (2015). *Confirmatory factor analysis for applied research* (2nd ed.). Guilford Press.
- Car, J., et al. (2025). Digital health competencies in medical education: An international consensus. *JAMA Network Open*. [doi:10.1001/jamanetworkopen.2024.53131](https://doi.org/10.1001/jamanetworkopen.2024.53131)
- Chen, F. F. (2007). Sensitivity of goodness of fit indexes to lack of measurement invariance. *Structural Equation Modeling*, 14(3), 464–504. <https://doi.org/10.1080/10705510701301834>
- CIRANO. (2024). *ICN – Indice de compétences numériques*. <https://cirano.qc.ca/fr/icn>
- Davis, D. A., et al. (2006). Accuracy of physician self-assessment compared with observed measures of competence. *JAMA*, 296(9), 1094–1102. <https://doi.org/10.1001/jama.296.9.1094>

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, 13(3), 319–340. <https://doi.org/10.2307/249008>

DeVellis, R. F., & Thorpe, C. T. (2022). *Scale development: Theory and applications* (5th ed.). Sage. ISBN :978-1544371764

Dewaele, J.-M., & MacIntyre, P. D. (2014). The two faces of Janus? Anxiety and enjoyment in the foreign language classroom. *Studies in Second Language Learning and Teaching*, 4(2), 237–274. <https://doi.org/10.14746/ssllt.2014.4.2.5>

Eccles, J. S., & Wigfield, A. (2002). Motivational beliefs, values and goals. *Annual Review of Psychology*, 53, 109–132. <https://doi.org/10.1146/annurev.psych.53.100901.135153>

Fan, C., & Wang, J. (2022). Development and validation of a questionnaire to measure digital skills of Chinese undergraduates. *Sustainability*, 14(6), 3539. <https://doi.org/10.3390/su14063539>

Ferrari, A. (2013). *DIGCOMP: A framework for developing and understanding digital competence in Europe*. European Commission.

Frehywot, S., Vovides, Y., Talib, Z., Mikhail, N., Ross, H., Wohltjen, H., & Scott, J. (2013). E-learning in medical education in resource constrained low- and middle-income countries. *Human Resources for Health*, 11, 4. <https://doi.org/10.1186/1478-4491-11-4>

Furr, R. M. (2018). *Psychometrics: An introduction* (3rd ed.). Sage. ISBN :978-1506339863

García-Robles, P., Cortés-Pérez, I., Nieto-Escámez, F. A., García-López, H., Obrero-Gaitán, E., & Osuna-Pérez, M. C. (2024). *Immersive virtual reality and augmented reality in anatomy education: A systematic review and meta-analysis*. *Anatomical Sciences Education*, 17(3), 514–528. <https://doi.org/10.1002/ase.2397>

Hatlevik, O. E., Guðmundsdóttir, G. B., & Loi, M. (2015). Examining factors predicting students' digital competence. *Journal of Information Technology Education: Research*, 14, 123–137. <https://doi.org/10.28945/2126>

Janssen, J., Stoyanov, S., Ferrari, A., Punie, Y., Pannekeet, K., & Sloep, P. (2013). Experts' views on digital competence. *Computers & Education*, 68, 473–481. <https://doi.org/10.1016/j.compedu.2013.06.008>

Kastorff, T., Sailer, M., Vejvoda, J., Schultz-Pernice, F., Hartmann, V., Hertl, A., ... Stegmann, K. (2023). Context-specificity to reduce bias in self-assessments: Comparing teachers' scenario-based self-assessment and objective assessment of technological knowledge. *Journal of Research on Technology in Education*, 55(6), 917–930. <https://doi.org/10.1080/15391523.2022.2062498>

Kline, R. B. (2016). *Principles and practice of structural equation modeling* (4th ed.). Guilford Press.

Langlois, J., et al. (2020). Spatial abilities and anatomy learning: A systematic review. *Anatomical Sciences Education*, 13(3), 235–250. <https://doi.org/10.1002/ase.1873>

Lardy, L. (2017). *Les facteurs qui influencent la réussite académique dans la filière technologique de l'université française* (Doctoral dissertation). Université Grenoble Alpes. <https://tel.archives-ouvertes.fr/tel-01690165>

Marsh, H. W., Morin, A. J. S., Parker, P. D., & Kaur, G. (2014). Exploratory structural equation modeling. *Annual Review of Clinical Psychology*, 10, 85–110. <https://doi.org/10.1146/annurev-clinpsy-032813-153700>

Messick, S. (1995). Validity of psychological assessment. *American Psychologist*, 50(9), 741–749. <https://doi.org/10.1037/0003-066X.50.9.741>

Minouei, M. A., Omid, A., Mirzaie, A., Mahdavi-fard, H., & Rahimi, A. (2024). *Effectiveness of virtual reality on medical students' academic achievement in anatomy: Systematic review*. BMC Medical Education, 24, Article 1407. <https://doi.org/10.1186/s12909-024-06402-1>

Ng, W. (2012). Can we teach digital natives digital literacy? *Computers & Education*, 59(3), 1065–1078. <https://doi.org/10.1016/j.compedu.2012.04.016>

Putnick, D. L., & Bornstein, M. H. (2016). Measurement invariance conventions and reporting. *Developmental Review*, 41, 71–90. <https://doi.org/10.1016/j.dr.2016.06.004>

Rodríguez-Miranda, F. P., Illanes-Segura, R., Ceada-Garrido, Y., & Infante-Moro, J. C. (2025). *Validation of a scale based on the DigComp framework on internet navigation and cybersecurity in older adults*. **Frontiers in Education**. <https://doi.org/10.3389/feduc.2025.1520929>

Roach, V. A., et al. (2020). Spatial ability and anatomy performance: A review. *Cureus*, 12(3), e7207. <https://doi.org/10.7759/cureus.7207>

Ryan, R. M., & Deci, E. L. (2000). Self-determination theory. *American Psychologist*, 55(1), 68–78. <https://doi.org/10.1037/0003-066X.55.1.68>

Sawchuk, K. (2020). *CIRANO Digital Skills Framework: Conceptual foundations and applications in higher education*. CIRANO.

Scheerder, A., van Deursen, A., & van Dijk, J. (2017). Determinants of Internet skills, uses and outcomes. *Telematics and Informatics*, 34(8), 1607–1624. <https://doi.org/10.1016/j.tele.2017.07.007>

Selwyn, N. (2022). *Education and technology: Key issues and debates* (3rd ed.). Bloomsbury Academic. ISBN: 9781350258785

Taber, K. S. (2018). The use of Cronbach's alpha when developing research instruments. *Research in Science Education*, 48, 1273–1296. <https://doi.org/10.1007/s11165-016-9602-2>

Tzafilkou, K., Perifanou, M., & Economides, A. A. (2022). Development and validation of students' digital competence scale. *International Journal of Educational Technology in Higher Education*, 19, 26.
<https://doi.org/10.1186/s41239-022-00330-0>

van Dijk, J. (2020). *The digital divide*. Polity Press. ISBN: 9781509534456

Vuorikari, R., Kluzer, S., & Punie, Y. (2022). *DigComp 2.2: The digital competence framework for citizens*. Publications Office of the European Union.
<https://doi.org/10.2760/115376>

Wang, X., Wang, Z., Wang, Q., & Chen, W. (2021). Development and validation of a university students' digital competence scale. *Journal of Computer Assisted Learning*.
<https://doi.org/10.1111/jcal.12575>

Warschauer, M. (2004). *Technology and social inclusion: Rethinking the digital divide*. MIT Press. ISBN: **9780262731737**

World Health Organization. (2016). *Process of translation and adaptation of instruments*.
<https://www.who.int>

APPENDICES

Appendix 1. ICNA Questionnaire – Version administered to students (original version)

A. PSYCHOSOCIAL FACTORS (Positivity scale / emotional profile)

The following statements describe how a person may think in certain situations. Please indicate the extent to which you agree with each statement.

Response scale:

- 1 = Strongly disagree
- 2 = Disagree
- 3 = Neither agree nor disagree
- 4 = Agree
- 5 = Strongly agree

Q1. I have great confidence in the future.

Q2. I am satisfied with my life.

Q3. I look to the future with hope and enthusiasm.

Q4. Overall, I am satisfied with myself.

Q5. At times, the future seems uncertain to me.

Q6. I feel that I have many things to be proud of.

Q7. In general, I have confidence in myself.

B. PERCEIVED SUCCESS IN THE ANATOMY COURSE

Regarding the anatomy course (for this academic year and beyond), please indicate the extent to which you agree with the following statements.

Response scale:

- 1 = Strongly disagree
- 2 = Disagree
- 3 = Neither agree nor disagree
- 4 = Agree
- 5 = Strongly agree

Q8. I am confident in my ability to learn this course.

Q9. I am able to achieve my goals in this course.

Q10. I feel capable of meeting the challenge of performing well in this course.

C. SOCIO-DEMOGRAPHIC DATA

Q11. Regarding the assessment of this course, I believe I can achieve at least the following final grade:

- 8/20
- 10/20
- 12/20
- 14/20

(no selection indicates an expected grade below 8/20)

Q12. Your age (in years).

Q13. Your gender:

- Male
- Female

Q14. In which track did you obtain your secondary school diploma (or equivalent)?

- Science (biology–chemistry or mathematics–physics)
- Latin–philosophy
- General education
- Business/commercial
- Other

Q15. What distinction did you obtain in your secondary school diploma (or equivalent)?

- High distinction ($\geq 75\%$)
- Distinction (70–74%)
- Pass (50–69%)

Q16. Have you ever repeated a year (primary, secondary, or university)?

- No
- Once
- Twice
- Three times
- More than three times

Q17. What is the highest level of education reached by your parents?

- None
- Secondary school diploma (or equivalent)
- Bachelor's degree (3 years post-secondary)
- Master's degree (5 years post-secondary)
- Advanced master's degree
- PhD

D. DIGITAL COMPETENCE AND ANATOMY LEARNING

Knowledge of digital environments in anatomy

Please indicate your level of agreement with the following statements.

Response scale:

- 1 = Strongly disagree
- 2 = Disagree

3 = Neither agree nor disagree

4 = Agree

5 = Strongly agree

Q18. It is important to know well the digital environment dedicated to teaching Anatomy.

Q19. The use of digital tools in anatomy classes will create a positive learning atmosphere.

Q20. Having a good mastery of digital anatomy learning tools will allow me to become a better medical practitioner.

Q21. The use of digital technologies will make anatomy courses more fun.

Q22. If I had the choice, I wouldn't use digital tools to learn Anatomy.

Q23. When using digital tools to study anatomy, making mistakes is normal.

Q24. Having a good mastery of digital anatomy learning tools will allow me to acquire anatomical knowledge more easily.

Q25. I would like to use digital tools to learn Anatomy.

Q26. I would never get bored when using digital Anatomy learning tools.

Q27. Using digital tools will allow me to learn interesting things.

Q28. Good knowledge of digital anatomy tools will facilitate my learning of other subjects in the curriculum.

Q29. Mastering digital tools in Anatomy will make me more competitive in the job market.

Q30. A good understanding of these tools will make me a reference person for other students.

Q31. Using digital tools to learn Anatomy is a waste of time.

Q32. I will feel comfortable using digital tools for learning anatomy.

E. DIGITAL LITERACY

Level of comfort with digital tools

Response scale:

1 = Not comfortable at all

2 = Slightly comfortable

3 = Neutral

4 = Comfortable

5 = Very comfortable

Q33. Mobile applications (smartphones, tablets).

Q34. Office suites (Microsoft Office, Apple iWork, etc.).

Q35. Management software packages (ERP, CRM, SCM).

Q36. Electronic Document Management (EDM).

Q37. Intranet.

Q38. Video conferencing tools (Teams, Zoom, WebEx).

Q39. Collaboration platforms (Teams, Slack, SharePoint).

Q40. Wikis and online text editors (Google Docs).

Q41. Forums and social media.

Q42. Project management software.

Q43. Instant messaging tools.

Q44. Artificial intelligence applications (ChatGPT, Gemini).

Self-assessment of digital competence

Response scale:

1 = Strongly disagree

2 = Disagree

3 = Neither agree nor disagree

4 = Agree

5 = Strongly agree

Q45. I can solve most technical problems I encounter.

Q46. I can easily learn how to use new digital tools.

Q47. I keep myself informed about important new digital tools.

Q48. I am familiar with many different digital tools.

Q49. I have the technical skills necessary to use digital tools.

Q50. I have good digital skills.

Q51. I am confident in my ability to search for information online.

Q52. I know the risks about online activities (cybersecurity and plagiarism).

Q53. I often get help from my colleagues through digital tools.

Q54. Digital tools allow me to better collaborate with my peers.

F. DIGITAL EQUIPMENT AND INTERNET USE

Q55. Do you own the following devices? (multiple answers possible)

- Smartphone
- Tablet
- Laptop
- Desktop computer
- Game console
- Smart TV

Q56–Q61. Are these devices for personal or shared use?

Q62. Average daily time spent using digital devices.

Q63. Average daily time spent online.

Q64. Internet access modes:

- Mobile data
- Public Wi-Fi
- Private Wi-Fi
- Wired connection (Ethernet)

APPENDIX 2. Final Factor Structure of the Anatomy Digital Competence Index (ICNA)

The exploratory factor analysis identified a five-factor structure reflecting distinct dimensions of digital competence and associated dispositions in anatomy learning. The items retained within each factor are presented below.

Factor 1 – Motivational value of digital technologies in anatomy

Item	Statement
Q18	It is important to know well the digital environment dedicated to teaching Anatomy.
Q19	The use of digital tools in anatomy classes will create a positive learning atmosphere.
Q20	Having a good mastery of digital anatomy learning tools will allow me to become a better medical practitioner.
Q24	Having a good mastery of digital anatomy learning tools will allow me to acquire anatomical knowledge more easily.
Q25	I would like to use digital tools to learn Anatomy.
Q27	Using digital tools will allow me to learn interesting things.
Q28	Good knowledge of digital anatomy tools will facilitate my learning of other subjects in the curriculum.
Q29	Mastering digital tools in Anatomy will make me more competitive in the job market.
Q32	I will feel comfortable using digital tools for learning anatomy.
Q33	Mobile applications (smartphones, tablets).
Q46	I can easily learn how to use new digital tools.

Factor 2 – Institutional uses of digital technologies

Item	Statement
Q34	Office suites (Microsoft Office, Apple iWork, etc.).
Q35	Management software packages (ERP, CRM, SCM).
Q36	Electronic Document Management (EDM).
Q37	Intranet.
Q38	Video conferencing tools (Teams, Zoom, WebEx).
Q39	Collaboration platforms (Teams, Slack, SharePoint).
Q42	Project management software.

Factor 3 – Positivity and academic self-efficacy

Item	Statement
Q1	I have great confidence in the future.
Q2	I am satisfied with my life.
Q3	I look to the future with hope and enthusiasm.
Q4	Overall, I am satisfied with myself.
Q6	I feel that I have many things to be proud of.
Q7	In general, I have confidence in myself.
Q8	I am confident in my ability to learn this course.
Q9	I am able to achieve my goals in this course.
Q10	I feel capable of meeting the challenge of performing well.

Factor 4 – Perceived digital competence

Item	Statement
Q45	I can solve most technical problems I encounter.
Q47	I keep myself informed about important new digital tools.
Q48	I am familiar with many different digital tools.
Q49	I have the technical skills necessary to use digital tools.
Q50	I have good digital skills.
Q51	I am confident in my ability to search for information online.
Q52	I know the risks about online activities (cybersecurity and plagiarism).

Factor 5 – Critical distance and ambivalence toward digital technologies

Item	Statement
Q5	At times, the future seems uncertain to me.
Q22	If I had the choice, I wouldn't use digital tools to learn Anatomy.
Q23	When using digital tools to study anatomy, making mistakes is normal.
Q31	Using digital tools to learn Anatomy is a waste of time.
Q41	Forums and social media.
Q43	Instant messaging tools.
Q44	Artificial intelligence applications (ChatGPT, Gemini).

APPENDIX 3. Items Removed During Factor Analysis

The following items were removed due to:

- low factor loadings
- cross-loadings
- unstable factor structure

Item	Reason
Q21	Insufficient factor loading
Q26	Low factor contribution
Q30	Unstable factor structure
Q40	Absence of dominant loading
Q53	Insufficient factor contribution
Q54	Loading below threshold

Etude 3 — Niveau processuel : usages des environnements numériques et engagement des apprenants

Préambule

Dans le prolongement des dimensions structurelles et individuelle, cette troisième partie s'intéresse à la dimension processuelle de l'apprentissage, c'est-à-dire aux usages effectifs au sein d'environnements numériques.

Elle repose sur l'idée que les effets des technologies ne peuvent être compris indépendamment de la manière dont les apprenants s'en emparent concrètement. Au-delà de la simple mise à disposition des outils, c'est la nature, l'intensité et la qualité des interactions avec ces environnements qui conditionnent les effets d'apprentissage.

L'**Article 2** traite spécifiquement de cette dimension à travers une étude multicentrique conduite dans des contextes pédagogiques contrastés en Europe et en Afrique subsaharienne.

C'est une étude qui repose sur un large échantillon de 2031 étudiants répartis en cinq cohortes issues de trois institutions d'enseignement supérieur, couvrant des formations et modalités d'intégration pédagogique variées.

Elle s'appuie notamment sur ARanatomy, un environnement pédagogique immersif en réalité augmentée spécifiquement développé dans le cadre d'une collaboration entre l'Université de Liège et l'Université du Québec à Trois-Rivières, constituant ainsi un outil original « home-made » intégré à cette recherche.

Elle adopte une approche intégrative articulant trois niveaux d'analyse : les usages effectifs des environnements numériques (mesurés à partir de données d'apprentissage instrumentées issues de différentes versions de l'application), les perceptions des étudiants —mesurées à l'aide de l'échelle WBLT (Web-Based Learning Tools) (Kay, 2014) — ainsi que leurs profils motivationnels évaluée sur base de la Self-Determination Theory, avec un questionnaire structuré en plusieurs dimensions (Ryan and Deci, 2000).

Afin de dépasser les limites des approches déclaratives classiques, l'étude intègre également une instrumentation progressive des usages (versions non instrumentées, partiellement instrumentées et pleinement instrumentées), permettant d'accéder à des indicateurs objectifs d'intensité et de profondeur d'engagement.

Dans cette perspective, l'objectif n'est pas uniquement d'évaluer l'efficacité du dispositif, mais de comprendre comment les usages, les perceptions et la motivation — en interaction avec le contexte pédagogique et les caractéristiques des apprenants — contribuent à expliquer les effets observés sur l'apprentissage.

Sur cette base, trois hypothèses sont formulées : (1) l'utilisation de l'environnement immersif est associée à l'engagement des étudiants, (2) l'intensité et les modalités d'usage sont associées à des profils motivationnels différenciés, et (3) les effets sur les performances varient en fonction du contexte pédagogique et du type de compétence évaluée.

Article 2: ***“Instrumenting Augmented Reality in Anatomy and Histology Education: What Student Usage Reveals About Engagement, Motivation and Learning in European and Sub-Saharan African Contexts”***

Soumis à la revue **Morphologie** le 10 avril 2026

Disponible en ligne depuis le 1^{er} juin 2026

DOI : <https://doi.org/10.1016/j.morpho.2026.101125>



Disponible en ligne sur

ScienceDirect
www.sciencedirect.com

Elsevier Masson France

EM|consulte
www.em-consulte.com



ORIGINAL ARTICLE

Instrumenting augmented reality in anatomy and histology education: What student usage reveals about engagement, motivation and learning in European and Sub-Saharan African contexts



D. Mutombo Mwembo^{a,b}, A. Fries^b, P. Bonnet^b,
A. Sul Ilunga Sul^a, O. Prygiel^b, A. Lagier^b, W. Arung Kalau^a,
S. Sobczak^c, M. Schyns^d, V. Defaweux^{b,*}

^a Department of Surgery, Faculty of Medicine, University Clinics of Lubumbashi, University of Lubumbashi, Lubumbashi, Democratic Republic of the Congo

^b Human Anatomy Laboratory, Department of Biomedical and Preclinical Sciences, Faculty of Medicine, University of Liège, Liège, Belgium

^c Department of Anatomy, Université du Québec à Trois-Rivières, Trois-Rivières, QC, Canada

^d HEC Liège, Management School of the University of Liège, Liège, Belgium

KEYWORDS

Augmented reality;
Anatomy education;
Histology education;
Learning analytics;
Visuospatial skills;
Student engagement

Summary The effectiveness of augmented reality (AR) in anatomy and histology education remains variable across literature, suggesting strong dependence on pedagogical context, learner characteristics, and conditions of use. ARAnatomy was developed as a mobile AR-learning environment to support spatial understanding of anatomical structures across multiple levels of organization, from macroscopic to histological, and required contextualized evaluation under authentic curricular conditions. This multicentric study involved 2,031 students across five cohorts from three institutions across Europe and Sub-Saharan Africa. Three successive versions of the application were deployed, differing in ergonomic maturity and level of usage instrumentation. Collected data included student perceptions (WBLT framework), motivation (Self-Determination Theory), objective usage traces, and performance outcomes when available. Descriptive, comparative, and correlational analyses were conducted, and usage profiles were identified using K-means clustering ($k = 3$). Perceptions of learning and design varied markedly across cohorts. Engagement differences between users and non-users were limited. Instrumented analyses showed that intensive and diversified use was associated with higher

* Corresponding author.

E-mail address: Valerie.defaweux@uliege.be (V. Defaweux).

visuospatial performance, whereas no effect was observed on immediate disciplinary performance. Usage intensity correlated positively with intrinsic motivation and positive emotions and negatively with amotivation. These findings indicate that the educational value of ARAnatomy depends primarily on its pedagogical integration, ergonomic maturity, and depth of use. AR was associated with higher visuospatial performance than with short-term academic performance, although no causal relationship could be established. Taking together, these results highlight the importance of analytics-informed and pedagogically aligned implementation in anatomy education.

© 2026 Elsevier Masson SAS. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Introduction

Over the past decade, extended reality technologies – including virtual reality (VR), augmented reality (AR), and hybrid environments – have increasingly been integrated into biomedical education. Systematic reviews highlight their potential to enhance student engagement, improve understanding of three-dimensional anatomical structures, and enrich learning experiences [1,2]. These tools appear particularly relevant in anatomy and histology, where learners must integrate spatial relationships across multiple levels of organization, from the macroscopic to the ultrastructural.

Despite this growing interest, empirical findings remain heterogeneous. While some studies report learning gains, others find little or no effect on immediate academic performance. This variability affects both knowledge-based outcomes and visuospatial abilities, which are often considered primary targets of immersive technologies [3,4]. Such discrepancies raise a central question: do these technologies enhance learning *per se*, or are their effects largely contingent upon the context in which they are implemented?

Accumulating evidence suggests that effectiveness is strongly conditioned by pedagogical integration. Factors such as instructional design, learner guidance, technological maturity, ergonomic stability, and cognitive load substantially modulate observed outcomes [5,6]. Consequently, AR and VR-based learning environments should not be viewed as uniform interventions but rather as tools whose impact depends on how they are embedded within educational contexts.

Beyond pedagogical design, individual learner characteristics play a critical role. Visuospatial abilities, prior digital experience, and motivational profiles influence adoption and depth of use [3,7,8]. Students with higher intrinsic motivation or stronger spatial skills tend to benefit more from three-dimensional representations, whereas amotivation and limited digital fluency are associated with superficial engagement and reduced learning benefits. These factors contribute to pronounced intra- and inter-cohort variability.

This dual dependence – on implementation context and learner characteristics – poses important methodological challenges. Few studies articulate macro-level curricular conditions, meso-level engagement patterns, and micro-level cognitive or motivational mechanisms within a single analytical framework. Moreover, most evaluations rely primarily on perception surveys, which provide limited insight

into actual usage behaviors. Learning-analytics research consistently shows discrepancies between declared and observed use, underscoring the need for objective instrumentation [9,10].

Another limitation of literature lies in the predominance of mono-centric studies conducted within highly homogeneous academic settings. Such approaches restrict generalizability and complicate the distinction between tool effects and contextual influences. Multicentric designs, by contrast, allow exploration of how institutional, cultural, and pedagogical variability modulates both usage patterns and learning outcomes.

Finally, studies combining perception, motivation, instrumented usage traces, and performance outcomes remain rare. Yet this integration is essential for understanding how AR- and VR-based learning environments are appropriate in authentic settings: which forms of use correspond to which learner profiles, how motivation shapes engagement, and under what conditions immersive technologies support visuospatial skills or disciplinary learning.

Responding to these gaps, the present multicentric study examines five cohorts from three institutions across diverse pedagogical contexts in anatomy and histology. It deploys successive versions of the same AR environment, differing in their level of instrumentation, enabling an integrated analysis of perceptions, motivation, engagement, usage behaviors, and performance. This design provides a robust framework for investigating how contextual conditions and individual differences shape the educational impact of AR.

Based on existing literature and preliminary observations, we formulated three hypotheses: (H1) the use of AR is positively associated with student engagement; (H2) usage intensity and modality are associated with differentiated motivational and engagement profiles; and (H3) the effects of AR-based learning environments on performance depend on the pedagogical context and the type of competence assessed. The specific application used in this study is described in detail in the Materials and Methods section.

Materials and methods

ARAnatomy: application design and technopedagogical framework

ARAnatomy is a mobile AR application designed to support learning in anatomy and histology through interactive three-dimensional representations displayed on a screen-

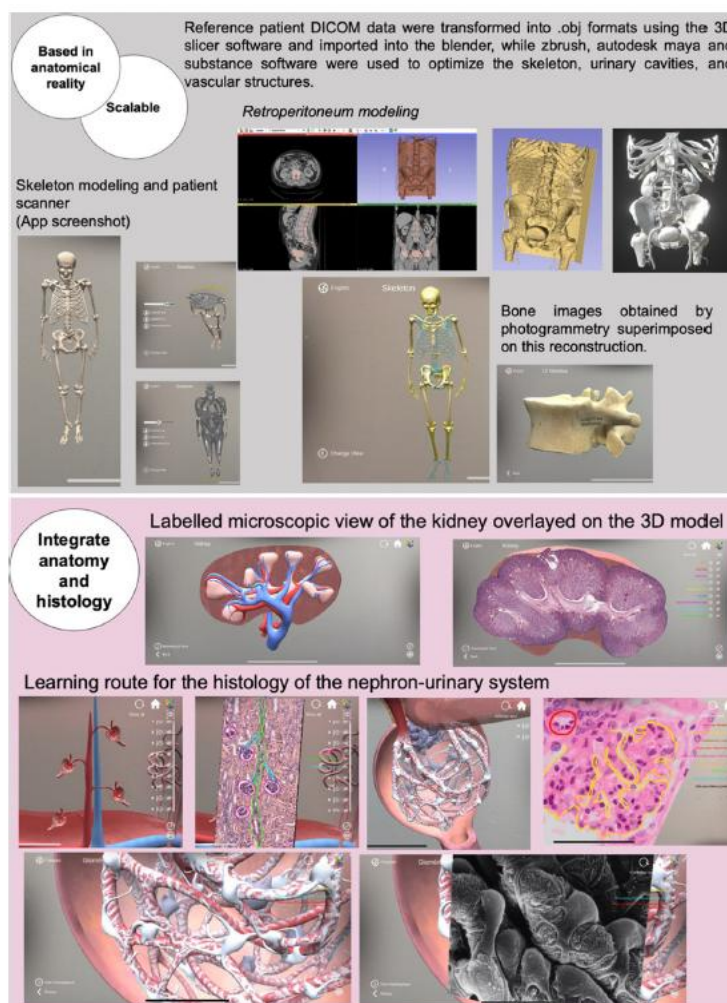


Figure 1 Multiscale anatomical modeling and integration of histological levels in ARAnatomy. The first panel illustrates the generation of anatomically accurate 3D models from patient-derived DICOM data, including segmentation and reconstruction of the skeletal framework, urinary cavities, and vascular structures, complemented by photogrammetry-based bone data. The second panel shows the integration of histological information, with superimposition of optical and electron microscopy images onto the anatomical models, enabling continuity between macroscopic organization and ultrastructural components. The application is freely available for download at the following links: <https://play.google.com/store/apps/details?id=com.ULiege.ARAnatomy&hl> (Android version) and <https://apps.apple.com/be/app/arnatomy-hec/id1523284550> (iOS version).

based interface, without full sensory immersion as defined in virtual reality environments. The application integrates anatomically accurate 3D models reconstructed from medical imaging (DICOM) data, complemented by histological content enabling navigation across multiple levels of biological organization, from macroscopic structures to ultrastructural components. In specific modules, optical and electron microscopy images are overlaid onto digital reconstructions to enhance spatial coherence (Fig. 1).

From its inception, ARAnatomy was conceived as an adaptable pedagogical environment suitable for both supervised and autonomous learning contexts. Its development

followed an iterative process involving educators, students, and developers, leading to successive refinements targeting interface stability, interaction fluidity, and cognitive ergonomics. Student feedback from early deployments informed major redesigns addressing manipulation difficulties, navigation clarity, and integration of learning pathways.

Instrumentation of usage and version evolution

Three levels of usage instrumentation were implemented across successive versions of the application:

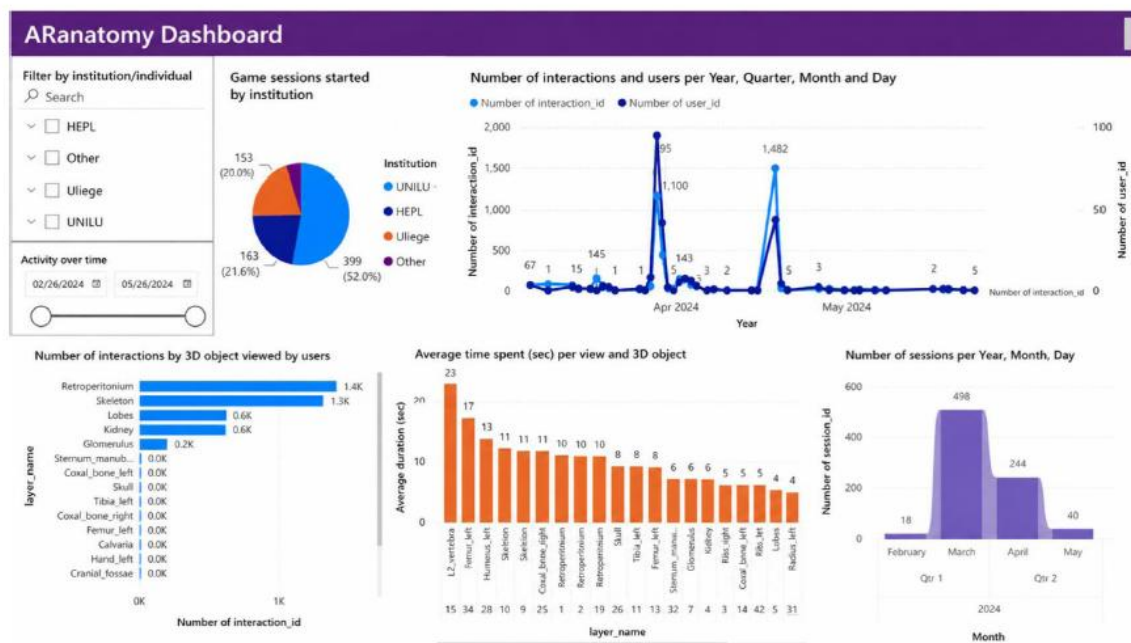


Figure 2 Dashboard of user interactions within the ARAnatomy application. Interactive dashboard summarizing user interactions within the ARAnatomy application. The dashboard displays temporal patterns of use, distribution of sessions and interactions across institutions, and indicators of content exploration (3D objects viewed, session frequency, and average interaction duration).

- version 0: non-instrumented use, without automated data collection;
- version 1: partial instrumentation, capturing session counts and accessed views;
- version 2: advanced instrumentation, including detailed metrics on AR interactions, exploration of histological layers, interaction duration, and navigation patterns across modes.

In instrumented versions of the application, usage data were automatically collected and visualized using Microsoft Power BI [11].

Based on these logs, synthetic indicators were computed to characterize usage intensity and depth (Fig. 2). To identify natural usage profiles, an unsupervised k-means clustering approach ($k = 3$) was applied, with the choice of k guided by considerations of interpretability and cluster stability, yielding three categories: low users, moderate users, and high users. These profiles were then used to examine relationships between usage behavior, motivation, perception, and performance.

In parallel, the application underwent a progressive process of ergonomic refinement across versions. While version 0 was characterized by notable usability limitations, subsequent iterations led to increasingly stable, structured, and user-friendly interactions. version 1 introduced initial improvements in interaction consistency and navigation, whereas version 2 reflects a more mature ergonomic design, with smoother navigation, standardized gestures, enhanced

visual transitions, and improved integration of layered anatomical and histological content.

Study context and description of the cohorts

The study included 2,031 students distributed across five cohorts from three higher education institutions, encompassing diverse programs and pedagogical contexts in anatomy and histology. ARAnatomy was integrated through heterogeneous usage modalities, ranging from introductory practical sessions to supervised competency-focused activities.

At the University of Liège (Belgium), three cohorts (cohorts 1–3) used version 0 of the application. Cohort 1 included first-year medical and dental students (BA1, $n = 315$), and cohort 2 comprised first-year biomedical sciences students (BA1, $n = 189$), both using ARAnatomy during introductory anatomy practicals. Cohort 3 consisted of second-year medical students (BA2, $n = 169$), who used the application in a supervised renal histology session. In this cohort, students were divided into two groups: the AM group completed a performance test before using the application, whereas the PM group completed it after use. Perception data were collected for all cohorts.

At the University of Lubumbashi (Democratic Republic of the Congo), cohort 4 included second-year medical students (BA2, $n = 1,200$) who used version 1 during introductory anatomy practicals. This version enabled partial usage instrumentation and the collection of perception, motivation, and pre/post test data.

Table 1 Evaluation questionnaire of ARanatomy application (adapted from WBLT).

Questionnaire Item
Learning
Working with ARanatomy helped me learn
The information provided by ARanatomy made my learning easier
The augmented reality (AR) component made my learning easier
Helped me learn the relationships between anatomical structures in 3D
Better visualization of the nephro-urinary system in space
The histological images included in the application helped me learn
The different magnification levels helped me learn
Design
The application interface was intuitive and easy to use
The 3D model was easy to manipulate (zoom and rotate)
The different features are easy to access
The screenshot and annotation features are an added value
Engagement
I found the application engaging
The application made learning fun
I would like to use the application again
I would show the application to my contacts

Evaluation questionnaire used to assess students' perceptions of the ARanatomy application, adapted from the Web-Based Learning Tools (WBLT) framework. The instrument covers three dimensions – learning, design, and engagement – and consists of items rated on a 4-point Likert scale ranging from strongly disagree to strongly agree.

At the Haute École de la Province de Liège (Belgium), cohort 5 consisted of first-year oral hygiene students (BA1, $n = 158$) who used version 2 during a supervised renal histology session. This fully instrumented version enabled detailed analysis of interaction behaviors alongside perception and motivation data.

Together, these cohorts represent substantial variability in institutional context, instructional design, and technological maturity.

Perception survey

Perception of the application was assessed using an adapted version of the Web-Based Learning Tools Framework [12], which evaluates three dimensions: learning (perceived learning support), design (usability and interface quality), and engagement (interest and user involvement). Items were tailored to ARanatomy's functionalities, focusing on 3D manipulation, spatial understanding, integration of histological content, and interface ergonomics. Lexical simplifications were applied for first-year cohorts to ensure item comprehension. All items were rated on a four-point Likert scale ranging from "Strongly disagree" (1) to "Strongly agree" (4) (Table 1).

Motivation assessment

Motivation was assessed in cohorts using instrumented versions of the application (cohorts 4 and 5) based on self-determination theory [7,8]. The questionnaire comprised 18 items distributed across four dimensions: intrinsic motivation, extrinsic motivation, amotivation, and positive emotions (Appendix 1 Table S1). Responses were collected on a four-point Likert scale, and dimension scores were summed to compute a global motivation index after reverse coding amotivation items. Motivation quartiles (Q1–Q4) were defined using empirical percentiles and used for subsequent analyses.

Study implementation and data availability

All cohorts contributed perception data. Usage analytics were available only for instrumented versions (cohorts 4 and 5). Pre-/post-test designs were implemented in two cohorts, aligned with their specific learning objectives: visuospatial ability assessments in cohort 4 and disciplinary histology performance in cohort 2. Analyses were therefore organized according to the type of available data within each cohort, rather than a single unified experimental design.

Statistical analyses

Statistical analyses were selected based on data distribution and variable type. Normality was assessed using the Shapiro-Wilk test. Descriptive statistics included means and standard deviations for normally distributed variables, medians and interquartile ranges for non-normal variables, and frequencies for categorical data.

Group comparisons employed parametric or non-parametric tests as appropriate. Associations between motivation, usage indicators, and performance were examined using Pearson or Spearman correlation coefficients, while relationships between motivational profiles and user categories were tested using χ^2 analyses. Statistical significance was set at $P < 0.05$, and effect sizes were reported when relevant to support interpretation of the results.

Results

Perception of the tool

Perception data were collected across all five cohorts using the Web-Based Learning Tools Framework (WBLT), covering the learning, design, and engagement dimensions. This enabled cross-cohort comparisons while accounting for differences in pedagogical context and application version.

Learning dimension

Perceptions of learning potential varied markedly between cohorts (Fig. 3). Cohort 1 reported high satisfaction, with over 85% positive responses ("Agree" or "Strongly agree"). In contrast, cohort 2 showed a less favorable profile, with a predominance of negative responses. Cohort 3 displayed an

Morphologie 110 (2026) 101125

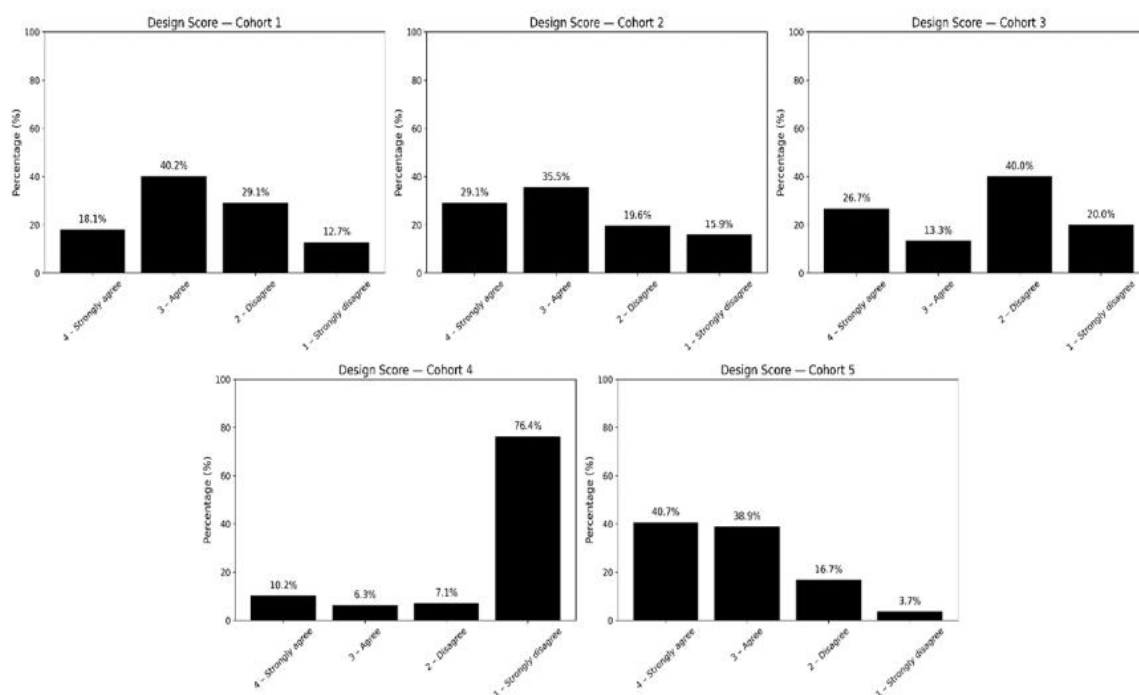


Figure 4 Distribution of agreement levels and perceptual profiles for the design dimensions across five evaluation cohorts. Percentages represent student responses on a 4-point Likert scale, illustrating contrasting perceptual profiles and marked differences in design appraisal between cohorts.

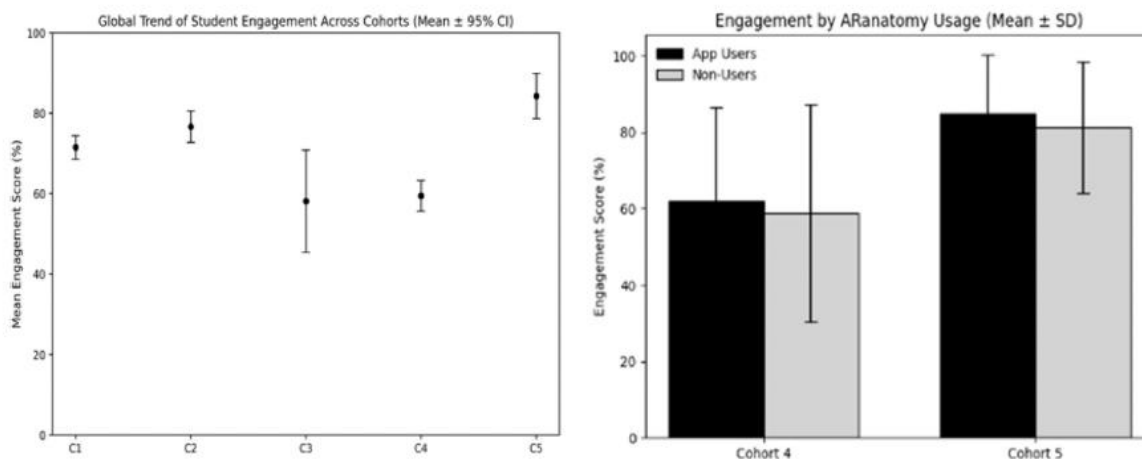


Figure 5 Student perception: overall trends across cohorts (C1–C5) and App/No App comparison in cohorts 4–5. Mean student engagement scores across the five cohorts (C1–C5), with 95% confidence intervals. The right panel presents mean engagement scores ($\pm$ SD) for ARAnatomy users and non-users in cohorts 4 and 5.

disciplinary performance, within the conditions of this assessment design (Fig. 6).

Visuospatial skills development (cohort 4)

Post-test performance revealed significantly higher visuospatial scores among ARAnatomy users compared with non-users (41.4% vs. 31.7%; Welch *t*-test, $P < 0.05$) (Fig. 7).

Usage intensity was positively correlated with post-test performance, particularly for the number of active days ($r = 0.30$; $P < 0.05$) and the number of views explored ($r = 0.29$; $P < 0.05$). Other indicators, such as session duration, showed positive but non-significant trends, suggesting a dose-response relationship between usage and performance.

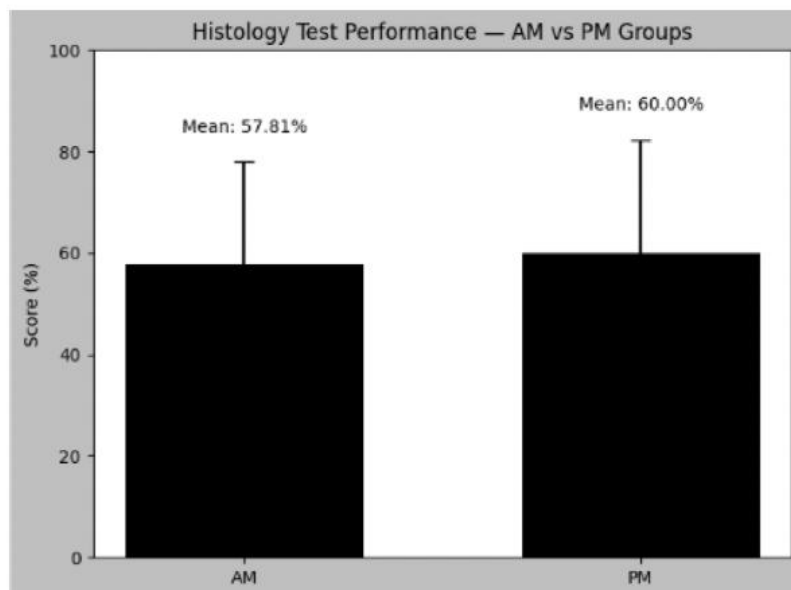


Figure 6 Cohort 2: distribution of histology test scores in AM and PM student groups. Bars represent mean test scores expressed as percentages for each group. Error bars indicate score dispersion around the mean. The figure summarizes the central tendency and variability of performance according to the assessment scheduling.

Pre-/post-test comparison (cohort 4)

Among students completing both tests ($n = 103$), descriptive trends suggested performance gains among users and a decline among non-users. However, paired t -tests showed no significant pre-/post-test differences within either group, nor significant differences in score changes between users and non-users. These results indicate that observed performance differences cannot be conclusively attributed to application use.

Motivational factors and application use (cohorts 4 and 5)

Overall motivation levels were high in both cohorts, with higher mean motivation observed in cohort 5. Users displayed slightly higher motivation scores than non-users, although these differences were descriptive only.

Analysis by motivation quartiles revealed a higher proportion of highly motivated students (Q4) among users compared with non-users in both cohorts. Intrinsic motivation and positive emotions were positively associated with usage intensity, whereas amotivation showed a consistent negative relationship with application use. In cohort 5, extrinsic motivation and positive emotions were strongly correlated with time spent in AR mode.

These patterns suggest that motivation is closely linked to actual engagement with the application, particularly its immersive features, and may act as a key modulator of usage behaviors.

Discussion

This multicentric study examined the educational impact of ARAnatomy across heterogeneous pedagogical contexts by combining perception data, motivation profiles, instru-

mented usage traces, and performance outcomes. Overall, the results show that the effects of ARAnatomy are neither uniform nor systematic. Rather, they depend strongly on (1) the pedagogical context of implementation, (2) students' motivation and actual intensity of use, and (3) the type of competence assessed. Beyond a tool-centered perspective, ARAnatomy should be understood as a flexible and instrumented learning environment whose effects emerge from the interaction between technology, context, and learner characteristics.

The findings partially support H1 and H2 and conditionally support H3. The use of ARAnatomy was not associated with higher perceived engagement *per se* (H1), but intensive and diversified use was associated with higher visuospatial performance and differentiated motivational profiles (H2). Finally, the effects on performance varied depending on pedagogical context and outcome type, with clear benefits for visuospatial skills but no measurable effect on immediate disciplinary performance (H3). This pattern suggests that AR technologies do not act as universal performance enhancers but as context-sensitive mediators of learning processes.

The primacy of pedagogical context (macro-level)

Marked differences in perception and engagement across cohorts highlight the central role of pedagogical context. Cohorts exposed to stable, ergonomically mature versions of the application within well-structured instructional settings reported highly positive evaluations, whereas less structured contexts using earlier versions yielded critical perceptions. These results confirm that immersive technologies cannot be evaluated independently of their pedagogical context. Instead, their educational value emerges through

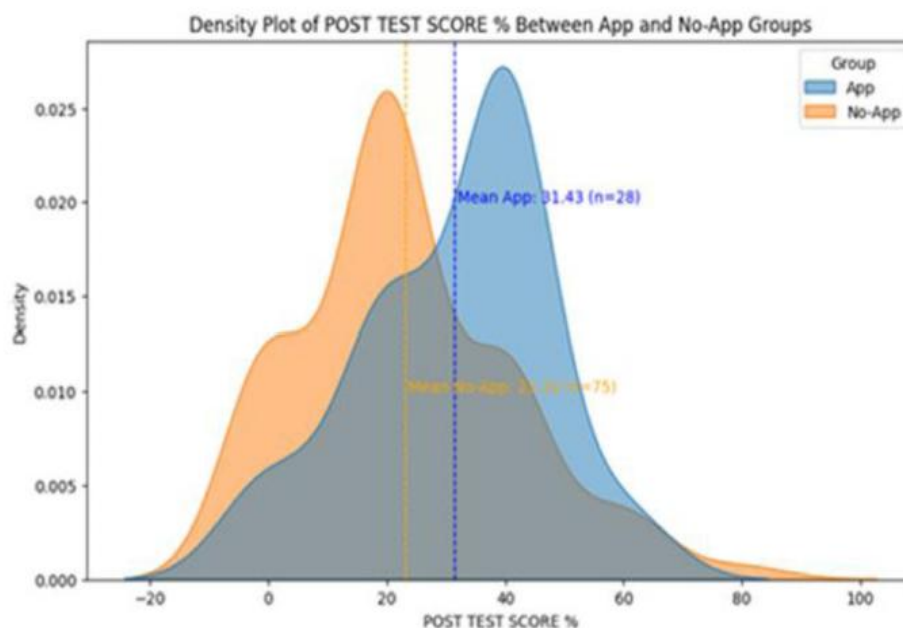


Figure 7 Distribution of post-test score by ARanatomy usage. Density curves represent score distributions for students who used the application (App) and those who did not (No-App). Vertical dashed lines indicate the mean post-test score for each group. The distribution for users is shifted toward higher scores compared with non-users.

alignment with instructional objectives, guidance, and curricular integration, as consistently reported in the literature [1,2].

Importantly, engagement levels appeared more closely tied to the broader learning environment than to the mere availability of AR. This aligns with evidence suggesting that immersive technologies act as amplifiers of existing pedagogical conditions rather than independent drivers of engagement.

Crucially, the variability observed across cohorts reflects not a limitation of the tool, but its pedagogical plasticity. ARanatomy adapts to diverse educational ecosystems, from resource-constrained contexts such as Lubumbashi – where it may compensate for limited access to physical materials – to well-equipped environments such as Liège, where it functions as a complementary and enrichment tool. This highlights its capacity to support differentiated instructional strategies rather than imposing a standardized model.

A key strength of this study lies in its multicentric design, which enables a structured comparison of contrasted educational contexts and their influence on perceptions, motivation, and usage patterns in augmented reality learning environments. The results do not reflect random variability across cohorts, but rather distinct and coherent profiles shaped by institutional context.

In the Belgian university cohorts (ULiège, C1–C3), results reveal marked heterogeneity in student perceptions, particularly in the learning and design dimensions of the WBLT framework. Profiles range from high levels of endorsement to more critical evaluations, suggesting that variations in pedagogical integration – from introductory exposure to more structured activities – combined with higher academic

expectations, contribute to differentiated experiences of the tool.

In contrast, the non-university higher education cohort (HEPL, C5) is characterized by highly positive and homogeneous perceptions across all WBLT dimensions, associated with elevated levels of intrinsic motivation and positive emotions. This profile suggests a strong alignment between the tool, pedagogical objectives, and supervision modalities, within a professionally oriented training context where digital tools are closely linked to future practice.

The cohort from the University of Lubumbashi (C4) presents a distinct configuration, characterized by more critical perceptions in the Learning dimension, yet accompanied by significant levels of engagement and usage. This apparent discrepancy between reported perceptions and actual usage suggests specific appropriation dynamics, in which digital tools may simultaneously represent both an opportunity for access and a challenge in terms of familiarity, usage conditions, and pedagogical mediation.

The combined analysis of WBLT perceptions, motivational profiles, and instrumented usage data thus reveals differentiated configurations across contexts: heterogeneity and high expectations in Belgian university settings, strong alignment and adherence in non-university higher education, and pragmatic appropriation in the Sub-Saharan African context. These findings indicate that augmented reality learning environments do not produce uniform effects, but rather act as amplifiers of the pedagogical and cultural conditions in which they are implemented.

This interpretation is consistent with prior research showing that the effectiveness of educational technologies depends strongly on implementation conditions and pedagogical alignment [13,14], particularly in heterogeneous or

resource-constrained contexts [15]. The multicentric nature of this study therefore constitutes not only a methodological strength but also an analytical framework for understanding contextual dynamics in digital learning environments.

Usage intensity and motivation as key modulators (meso-level)

While simple comparisons between users and non-users yielded limited differences, instrumented analyses revealed that depth and regularity of use represent critical differentiators. Intensive users demonstrated higher visuospatial performance and more favorable motivational profiles. Intrinsic motivation and positive emotions were consistently associated with richer exploration of the application, whereas amotivation was associated with minimal use.

These findings are in line with Self-Determination Theory [7,8], which posits that intrinsic motivation fosters autonomous and sustained engagement. In this regard, ARanatomy's interactive and spatial affordances appear to support learning only when students actively invest in exploration rather than passively interact with the tool. Thus, effectiveness depends on the quality of engagement rather than exposure alone. This shifts the interpretation from access to appropriation: the presence of the tool is insufficient, and its educational value is contingent upon active, sustained, and meaningful use. ARanatomy therefore operates as an affordance-rich environment whose potential is actualized through learner engagement.

Differential effects on learning outcomes (micro-level)

The study highlights differing patterns between disciplinary performance and visuospatial skills. Immediate academic performance in histology was not influenced by ARanatomy use, particularly in contexts involving short, one-time exposure and highly structured assessments. In contrast, visuospatial abilities – closely aligned with the cognitive affordances of AR – were higher among users, with stronger effects observed as usage intensity increased.

This pattern aligns with previous research showing that 3D and AR environments preferentially support spatial cognition rather than declarative knowledge acquisition [3,4]. This suggests that AR may be more effective when the targeted competence directly matches the underlying cognitive processes supported by the technology. These findings reinforce the importance of constructive alignment between technological affordances and targeted learning outcomes, positioning ARanatomy as particularly relevant for tasks involving spatial reasoning and mental manipulation of anatomical structures.

Selection effects and limits of causal inference

Although users outperformed non-users in visuospatial tasks, pre-test differences and the absence of significant pre-/post-test effects prevent causal attribution. Students with stronger initial visuospatial abilities may also be more inclined to adopt immersive environments, resulting in a

selection effect. Thus, these associations should not be interpreted as causal.

This highlights the need to account for learner characteristics, such as digital fluency and perceived competence, when evaluating immersive technologies. Future studies should adopt designs explicitly addressing self-selection mechanisms and longitudinal learning trajectories.

Methodological contributions and practical implications

This study highlights the value of combining multicentric designs with learning analytics data. Instrumented usage traces enable objective identification of learner profiles and reveal engagement mechanisms that remain invisible in self-reported data alone [9,10].

Practically, ARanatomy should be integrated into structured pedagogical strategies promoting sustained and guided use. Occasional or unguided exposure is unlikely to yield measurable learning gains, whereas structured integration targeting spatial reasoning may leverage the technology's full educational potential. More broadly, these findings support a shift from technology adoption to pedagogical orchestration, where immersive tools are embedded within intentional learning designs tailored to specific contexts and learner needs.

Conclusion

ARanatomy functions not as a universal learning enhancer but as an instrumented learning environment whose impact depends on context, motivation, and usage intensity. Its strongest contribution lies in supporting visuospatial cognition, while effects on immediate disciplinary performance remain conditional and context-dependent. Its added value lies in its flexibility and adaptability across diverse educational settings, enabling context-sensitive implementations ranging from compensatory to enrichment functions. These findings call for pedagogically aligned, analytics-informed deployment of AR technologies in anatomy and histology education.

Use of artificial intelligence

The authors used artificial intelligence tools to assist with language editing, English translation, and formatting of the manuscript. These tools were not used to generate scientific content, interpret data, or draw conclusions. All scientific aspects of the work were developed and validated by the authors.

Ethics statement

These datasets were collected and processed in accordance with the Humanities and Social Sciences Ethics Committee (Ref. 2023-18), and in compliance with the European General Data Protection Regulation.

Authors' contribution

Dr. David Mutombo Mwembo: conceptualization, investigation, writing – original draft, methodology, validation, visualization, writing – review & editing, project administration.

Dr. Allyson Fries: investigation, writing – original, draft, methodology, validation, visualization, writing – review & editing, supervision.

Prof. Pierre Bonnet: funding acquisition, writing – review & editing, project administration, supervision.

Dr. Arsène Sul Ilunga Sul: investigation, methodology, writing – review & editing, formal analysis.

Mr. Olivier Prygiel: investigation, methodology, writing – review & editing, formal analysis.

Prof. Aude Lagier: funding acquisition, writing – review & editing, project administration, supervision.

Prof. Willy Arung Kalau: funding acquisition, project administration, supervision.

Prof. Stéphane Sobczak: funding acquisition, writing – review & editing, supervision.

Prof. Michael Schyns: conceptualization, investigation, funding acquisition, methodology, visualization, formal analysis, supervision.

Prof. Valérie Defaweux: corresponding author, submitting author, conceptualization, investigation, funding acquisition, writing – original draft, methodology, validation, visualization, writing – review & editing, formal analysis, project administration, supervision, resources.

All authors have read and approved the final manuscript.

Funding

This work was supported by the Anatomy Laboratory of the University of Liège [ARES Project-PFS-2022-RDC-VanSintJan: University of Lubumbashi, University of Liège, and Université Libre de Bruxelles]; by The Université du Québec à Trois-Rivières [FIP (*fonds d'innovation pédagogique*)]; and by the University of Liège [*fonds de soutien à l'enseignement ULiège*].

Disclosure of interest

The authors declare that they have no competing interest.

Acknowledgments

The authors would like to thank Mrs. Marie Goffin for her valuable assistance in data collection and statistical analysis and Mr. Alexis Jacquemin (Michael Shyns' team) for his contributions to the application's graphic design and visual representation of anatomically relevant structures in virtual reality.

Appendix 1. Table S1 Motivation survey items categorized by motivational pillar

Item	Question	Motivation pillar
Q1	For me, it is important to be familiar with digital learning environments dedicated to anatomy education because it allows me to stay up to date with modern developments	Intrinsic motivation
Q2	The use of digital tools in anatomy education creates a positive working atmosphere	Positive emotions
Q3	It is important for me to master digital learning environments in anatomy because this will help me become a better physician	Extrinsic motivation
Q4	Using digital tools in anatomy teaching makes the course more enjoyable	Positive emotions
Q5	If I had the choice, I would not use digital environments to learn anatomy	Amotivation
Q6	When using digital tools to study anatomy, making mistakes is normal	Positive emotions
Q7	It is important for me to master digital anatomy learning environments because they help me acquire knowledge more easily	Intrinsic motivation
Q8	I enjoy using digital environments when learning anatomy	Positive emotions
Q9	I never feel bored when using digital anatomy learning environments	Positive emotions
Q10	By using digital environments for learning anatomy, I have learned interesting things	Positive emotions
Q11	It is important for me to be familiar with digital anatomy learning environments because they facilitate my learning in other subjects of the curriculum	Intrinsic motivation
Q12	During class, I feel proud of my achievements	Positive emotions

Q13	In my academic journey, we laugh a lot	Positive emotions
Q14	It is important for me to master digital anatomy learning environments because it will make me more competitive in the job market	Extrinsic motivation
Q15	It is cool to use digital anatomy learning environments	Positive emotions
Q16	It is important for me to master digital learning environments in order to become a reference person in my university and among other students	Extrinsic motivation
Q17	I think that using digital anatomy learning environments is a complete waste of time	Amotivation
Q18	I feel comfortable using digital anatomy learning environments	Positive emotions

Items Q5 and Q17 (Amotivation) were reverse scored in the calculation of the global motivation index. Intrinsic and extrinsic motivation items were adapted to reflect the specific context of digital anatomy learning. The questionnaire was administered in French and translated into English for reporting purposes.

References

- [1] García-Robles P, Cortés-Pérez I, Nieto-Escámez FA, García-López H, Obrero-Gaitán E, Osuna-Pérez MC. Immersive virtual reality and augmented reality in anatomy education: a systematic review and meta-analysis. *Anatom Sci Educ* 2024;17(3):514–28, <http://dx.doi.org/10.1002/ase.2397>.
- [2] Tene T, Bonilla García N, Coello-Fiallos D, Borja M, Vacacela Gomez C. A systematic review of immersive educational technologies in medical physics and radiation physics. *Front Med* 2024;11:1384799, <http://dx.doi.org/10.3389/fmed.2024.1384799>.
- [3] Bogomolova K, Hierck BP, Looijen AEM, Pilon JNM, Putter H, Wainman B, et al. Stereoscopic three-dimensional visualisation technology in anatomy learning: a meta-analysis. *Med Educ* 2021;55(3):317–27, <http://dx.doi.org/10.1111/medu.14352>.
- [4] Koh MY, Tan GJS, Mogali SR. Spatial ability and 3D model colour-coding affect anatomy performance: a cross-sectional and randomized trial. *Sci Rep* 2023;13:7879, <http://dx.doi.org/10.1038/s41598-023-35046-2>.
- [5] Masoumian Hosseini ST, Qayumi K, Pourabbasi A, Haghighi E, Sabet B, Koohpaei A, et al. Are we ready to integrate modern technologies into the medical curriculum? A systematic review. *Discov Educ* 2025;4(1):114, <http://dx.doi.org/10.1007/s44217-025-00521-7>.
- [6] Tzortzoglou F, Sofos A. Evaluating the usability of mobile-based augmented reality applications for education: a systematic review. In: Bratitsis T, editor. *Research on e-learning and ICT in education*. Springer; 2023. p. 105–35, http://dx.doi.org/10.1007/978-3-031-34291-2_7.
- [7] Ryan RM, Deci EL. Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *Am Psychol* 2000;55(1):68–78, <http://dx.doi.org/10.1037/0003-066X.55.1.68>.
- [8] Ryan RM, Deci EL. Intrinsic and extrinsic motivation from a self-determination theory perspective: definitions, theory, practices, and future directions. *Contemp Educ Psychol* 2020;61:101860, <http://dx.doi.org/10.1016/j.cedpsych.2020.101860>.
- [9] Sakr A, Abdullah T. Virtual, augmented reality and learning analytics impact on learners and educators: a systematic review. *Educ Inf Technol* 2024;29(15):19913–62, <http://dx.doi.org/10.1007/s10639-024-12602-5>.
- [10] Singh M, Bangay S, Sajjanhar A. Augmented reality enhanced analytics for education: a systematic review. *J Learn Anal* 2025;12(3):126–55, <http://dx.doi.org/10.18608/jla.2025.8447>.
- [11] Microsoft Corporation. Microsoft power BI desktop [computer software]; 2024 [<https://powerbi.microsoft.com/>].
- [12] Kay R. Evaluating learning, design, and engagement in web-based learning tools (WBLTs): the WBLT Evaluation Scale. *Comput Hum Behav* 2011;27(5):1849–56, <http://dx.doi.org/10.1016/j.chb.2011.04.007>.
- [13] Kirkwood A, Price L. Technology-enhanced learning and teaching in higher education: what is “enhanced” and how do we know? A critical literature review. *Learn Media Technol* 2014;39(1):6–36, <http://dx.doi.org/10.1080/17439884.2013.770404>.
- [14] Selwyn N. *Education and technology: key issues and debates*, 2nd ed. Bloomsbury Academic; 2017.
- [15] Rodríguez-Segura D. EdTech in developing countries: a review of the evidence. *World Bank Res Observ* 2021;36(2):171–203, <http://dx.doi.org/10.1093/wbro/lkab011>.

Discussion générale

L'analyse présentée dans cette discussion générale vise à dépasser une lecture encore largement répandue des effets du numérique en enseignement de l'anatomie humaine, fondée sur une logique implicitement technocentrée. Les résultats de cette thèse montrent en effet que les dispositifs numériques ne produisent pas d'effets pédagogiques intrinsèques : leurs effets sur l'apprentissage ne peuvent être compris qu'à la condition de prendre en compte les contextes institutionnels dans lesquels ils sont déployés, les profils des apprenants qui les mobilisent et les usages effectifs qui en sont faits.

Ce constat conduit à remettre en question une conception instrumentale de l'efficacité pédagogique, qui attribuerait aux technologies éducatives un pouvoir causal direct sur les apprentissages. En cohérence avec les travaux critiques sur le déterminisme technologique (Clark, 1983 ; 1994 ; Cuban, 2001 ; Selwyn, 2017), cette thèse montre que le numérique ne constitue ni une solution universelle ni un levier pédagogique autonome, mais un ensemble d'outils dont les effets dépendent étroitement des conditions de leur intégration pédagogique et institutionnelle.

Ainsi donc, cette discussion générale ne vise pas à reprendre de manière séquentielle les analyses conduites article par article, mais à proposer une lecture transversale et intégrative des résultats, en s'appuyant sur leur mise en regard synthétique présentée en annexe 2. Elle s'inscrit ainsi directement dans le cadre de la question de recherche et de l'hypothèse générale formulées en introduction, en examinant dans quelle mesure les effets observés peuvent être interprétés comme le produit des interactions entre contexte pédagogique, profils d'apprenants et usages effectifs des technologies.

A partir des résultats empiriques issus de trois articles complémentaires, cette discussion générale propose ainsi une lecture interactionniste des effets du numérique en anatomie humaine. Elle s'organise autour de trois niveaux d'analyse articulés :

1. un niveau structurel, qui met en évidence le rôle déterminant des contextes pédagogiques et institutionnels ;
2. un niveau individuel, centré sur les compétences numériques disciplinaires et les profils d'apprenants ;
3. un niveau processuel, qui analyse les usages effectifs, l'engagement et les dynamiques d'appropriation des dispositifs numériques.

Ces trois dimensions, introduites dans le modèle conceptuel, sont ici analysées dans leur articulation, afin de rendre compte des interactions dynamiques qui structurent les effets observés.

1 DEPASSER UNE LECTURE TECHNOCENTREE DE L'APPRENTISSAGE EN ANATOMIE HUMAINE

Une part importante de la littérature en technologies éducatives a longtemps cherché à évaluer les effets du numérique sur l'apprentissage en termes de gains de performance mesurables, en postulant implicitement une relation causale entre l'introduction d'un outil et l'amélioration des résultats académiques. Cette approche, qualifiée de technocentrée, a été largement critiquée dès les travaux fondateurs de Clark (1983, 1994), qui ont montré que les médias ne constituent pas des agents explicatifs autonomes de l'apprentissage, mais des

véhicules de l’instruction, dont les effets dépendent des méthodes pédagogiques qu’ils supportent.

Les recherches ultérieures ont renforcé cette critique. Cuban (2001) a mis en évidence l’écart récurrent entre les promesses associées aux innovations technologiques et leurs usages réels dans les institutions éducatives, tandis que Selwyn (2017) a souligné le caractère profondément social, culturel et politique des technologies éducatives. Dans le contexte de l’enseignement supérieur, Kirkwood et Price (2014) insistent sur le fait que l’efficacité du numérique repose avant tout sur l’alignement entre objectifs pédagogiques, modalités d’évaluation et usages effectifs des outils.

Les résultats de cette thèse s’inscrivent pleinement dans cette perspective critique. En montrant que des dispositifs numériques identiques, mis en œuvre selon un protocole expérimental comparable, produisent des effets différenciés selon les institutions, les cohortes et les profils d’apprenants, ils invalident toute lecture simpliste de l’efficacité du numérique. Ces variations ne sauraient être interprétées comme des artefacts méthodologiques ou des limites expérimentales : elles constituent au contraire un résultat central, révélateur du caractère situé et conditionnel des effets du numérique en anatomie humaine.

Dépasser une lecture technocentrée implique ainsi de déplacer la focale analytique : il ne s’agit plus de se demander si un outil numérique « fonctionne » en soi, mais d’analyser dans quelles conditions, pour quels apprenants et à travers quels usages il est susceptible de soutenir des apprentissages pertinents. Cette posture constitue le cadre théorique général dans lequel s’inscrivent les sections suivantes de la discussion.

2 RÔLE DU CONTEXTE PÉDAGOGIQUE ET INSTITUTIONNEL DANS LA CONFIGURATION DES EFFETS DU NUMÉRIQUE

Le rôle du contexte pédagogique et institutionnel dans l’analyse des effets du numérique en anatomie humaine ne peut être réduit à une variable d’arrière-plan ou à un simple facteur de variation des résultats. Les données issues des trois études, mises en perspective dans le tableau de synthèse (annexe 2), montrent de manière convergente que des dispositifs numériques comparables ne produisent pas des effets homogènes, mais s’inscrivent dans des configurations pédagogiques différenciées, propres à chaque contexte d’implémentation.

Dans cette perspective, les effets observés ne peuvent être interprétés comme des propriétés intrinsèques des technologies, mais comme le produit de systèmes d’interactions situés, associant dispositifs, pratiques pédagogiques, cadres institutionnels et caractéristiques des apprenants. Cette lecture rejoint les travaux en technologies éducatives qui soulignent que les environnements d’apprentissage doivent être appréhendés comme des systèmes socio-techniques, au sein desquels les effets du numérique dépendent de leur intégration dans des contextes pédagogiques spécifiques (Kirkwood & Price, 2014 ; Selwyn, 2017 ; Cuban, 2001 ; Gros, 2016). Ces perspectives s’inscrivent dans un ensemble de cadres théoriques convergents — tels que la théorie de l’activité (Engeström, 1987), les approches en termes d’écologies de l’apprentissage (Barron, 2006) ou encore les analyses des systèmes socio-techniques — qui considèrent les situations d’apprentissage comme des configurations dynamiques associant outils, acteurs, pratiques et contraintes institutionnelles.

Dans cette optique, les effets des technologies éducatives ne peuvent être dissociés des modalités concrètes de leur mise en œuvre, ni du degré de structuration pédagogique qui les

accompagne (Kirschner & De Bruyckere, 2017). Les travaux de Cuban (2001) et Selwyn (2017) montrent en particulier que l'écart entre les potentialités des technologies et leurs effets observés s'explique largement par les contextes d'usage et les pratiques effectives dans lesquelles elles s'inscrivent.

Ainsi, parler de "configuration pédagogique" permet de rendre compte du fait que les dispositifs numériques n'agissent jamais isolément, mais prennent sens et produisent des effets au sein d'agencements particuliers, caractérisés par un certain degré d'alignement entre objectifs d'apprentissage, modalités d'enseignement, formes d'évaluation et conditions institutionnelles. Cette approche conduit à déplacer l'analyse des effets du numérique d'une logique centrée sur les outils vers une compréhension située des conditions dans lesquelles ces outils peuvent — ou non — soutenir des apprentissages en anatomie humaine.

2.1 Le contexte institutionnel comme déterminant majeur des effets du numérique

L'un des résultats majeurs de l'étude préliminaire réside dans la comparaison interinstitutionnelle menée entre des établissements d'enseignement supérieur en Belgique (université de Liège et haute école de la province de Liège) et en République Démocratique du Congo (université de Lubumbashi). Cette comparaison met clairement en évidence que des dispositifs numériques conçus et déployés dans un cadre expérimental identique ne produisent pas des effets homogènes sur les apprentissages en anatomie humaine.

Ces différences s'observent en premier lieu au niveau des conditions initiales d'entrée dans l'apprentissage. Les résultats montrent que les cohortes se distinguent par leurs profils initiaux : les étudiants de l'UNILU déclarent des niveaux de compétence numérique en anatomie plus élevés, tandis que ceux d'ULiège présentent de meilleures aptitudes visuospatiales de départ. Ces différences ne sont pas anecdotiques ; elles dessinent des contextes d'apprentissage déjà contrastés, qui orientent et structurent les modalités d'appropriation des dispositifs numériques.

Les effets du contexte se manifestent ensuite de manière très nette dans les performances académiques. À dispositif expérimental comparable, les performances immédiates diffèrent selon les institutions. A l'UNILU, les taux de réussite restent globalement faibles et peu différenciés selon les modalités pédagogiques, oscillant entre 21,6 % et 28 %. A l'ULiège, les performances immédiates sont plus élevées, atteignant 35,3 %, avec un avantage plus marqué pour les modalités actives. A la HEPL, les résultats apparaissent plus instables, notamment pour certaines modalités virtuelles actives. Une association significative entre institution et réussite immédiate est par ailleurs observée.

Ces écarts, au-delà de leur valeur descriptive, doivent être interprétés comme des indicateurs de configurations pédagogiques distinctes, plutôt que comme de simples variations de performance.

Surtout, le contexte institutionnel continue à produire des effets au-delà de l'immédiateté de la tâche. Après ajustement sur les scores initiaux, les performances différées à 24 heures demeurent significativement liées à l'institution : les étudiants de l'ULiège obtiennent des scores supérieurs à ceux de l'UNILU, tandis que ceux de la HEPL présentent des performances inférieures à ces derniers. Ces résultats indiquent que la rétention des connaissances ne dépend pas uniquement de la modalité pédagogique choisie, mais du cadre institutionnel dans lequel celle-ci est intégrée.

L'article 2 (étude 3) confirme cette lecture en montrant que, pour un même outil (ARanatomy), les perceptions d'apprentissage, de design et d'engagement varient fortement selon les cohortes. Les différences observées sont statistiquement très marquées pour la dimension apprentissage ($\chi^2(12) = 757,1$, $p < .001$), avec des profils allant d'une adhésion quasi unanime à des évaluations majoritairement négatives. Ces écarts ne peuvent être imputés à la seule présence de l'application ; ils renvoient plus largement à la combinaison entre maturité ergonomique, cadrage pédagogique et environnement institutionnel.

Pris dans leur ensemble, ces résultats permettent d'identifier des configurations pédagogiques différenciées selon les contextes institutionnels. Dans certains contextes, notamment à l'UNILU, le numérique apparaît comme une ressource fortement valorisée par les étudiants, mais dont les effets restent contraints par les conditions pédagogiques et structurelles d'implémentation. À l'inverse, dans des contextes comme celui de l'ULiège, les dispositifs numériques s'inscrivent dans des environnements pédagogiques plus structurés, caractérisés par une meilleure articulation entre modalités d'enseignement, compétences initiales des apprenants et objectifs d'apprentissage. Entre ces deux pôles, certains contextes intermédiaires, tels que la HEPL, se distinguent par une plus grande variabilité des effets observés, traduisant une moindre stabilisation des configurations pédagogiques.

Ces divergences ne peuvent être expliquées par la seule disponibilité des outils numériques ni par leurs caractéristiques techniques. Elles reflètent des organisations pédagogiques distinctes, des traditions disciplinaires spécifiques et des contraintes structurelles différenciées.

Les résultats empiriques de cette thèse confirment pleinement cette perspective : les performances observées dépendent avant tout du degré de cohérence entre les dispositifs numériques, les curricula et les cadres institutionnels dans lesquels ils s'insèrent.

2.2 Du dispositif numérique isolé à l'écosystème pédagogique en anatomie

Dans ce travail, la notion d'écosystème pédagogique est mobilisée dans un sens descriptif pour désigner l'ensemble des composantes du système d'apprentissage — ressources, acteurs, outils, pratiques et contraintes institutionnelles — tandis que celle de configuration pédagogique est utilisée comme un outil analytique permettant d'interpréter la manière dont ces composantes s'articulent concrètement pour produire des effets différenciés. Cette distinction permet d'éviter toute confusion entre la description des environnements d'apprentissage et l'analyse des mécanismes par lesquels ceux-ci donnent forme aux effets du numérique. Cette distinction s'inscrit dans les approches en technologies éducatives qui conçoivent les environnements d'apprentissage comme des systèmes complexes et situés, associant dimensions sociales, techniques et pédagogiques (Selwyn, 2017 ; Cuban, 2001 ; Barron, 2006).

La lecture conjointe des résultats montre que les effets du numérique en anatomie humaine ne peuvent être interprétés à l'échelle du dispositif pris isolément. Dans l'étude préliminaire, les différences de performance observées entre modalités (virtuelle, haptique, active ou passive) ne sont ni systématiques ni homogènes d'une institution à l'autre. Les modalités actives apparaissent plus favorables dans certains contextes, notamment à l'ULiège, alors que dans d'autres, en particulier à l'UNILU, les écarts entre modalités sont plus faibles et certaines modalités passives obtiennent des résultats comparables, voire supérieurs.

L'article 2 renforce cette interprétation en montrant que l'exposition à un même outil ne suffit pas à produire des effets homogènes sur l'expérience d'apprentissage. Dans certaines

cohortes, aucune différence significative d'engagement n'est observée entre utilisateurs et non-utilisateurs de l'application, suggérant que l'environnement pédagogique global exerce une influence plus déterminante que la simple utilisation du dispositif.

L'article 1 (étude 2) apporte un éclairage complémentaire en montrant que les usages et les dispositions à l'égard du numérique sont eux-mêmes structurés par les contextes institutionnels. Les étudiants de l'UNILU obtiennent des scores significativement plus élevés sur l'ensemble des cinq dimensions de l'ICNA, avec des tailles d'effet allant de modérées à fortes par rapport aux contextes belges. Le contexte institutionnel agit ainsi non seulement sur les apprentissages observés, mais également sur les dispositions qui préparent l'entrée dans les environnements numériques : valeur accordée au numérique, usages institutionnels, sentiment de compétence, positivité et distance critique.

Les effets observés relèvent ainsi moins des caractéristiques intrinsèques de l'outil que de la qualité de son intégration dans un environnement d'apprentissage donné. Ils traduisent des configurations pédagogiques situées, façonnées par l'articulation entre les pratiques enseignantes, les modalités d'évaluation, les ressources institutionnelles disponibles et les profils des apprenants. Cette lecture interactionnelle s'inscrit dans le prolongement de la théorie de l'activité développée par Yrjö Engeström (1987) ainsi que des approches de design pédagogique structuré proposées par Paul A. Kirschner et Pedro De Bruyckere (2017).

2.3 Contextes à ressources limitées et limites de la transférabilité pédagogique

La comparaison entre les contextes belge et congolais apporte un éclairage particulièrement précieux sur la question de la transférabilité des dispositifs numériques. Les résultats de l'étude préliminaire montrent que, malgré un protocole expérimental comparable, les performances immédiates et différées restent significativement associées à l'institution, indiquant que les effets observés ne sont pas universels, mais étroitement dépendants des conditions locales d'implémentation.

L'article 1 suggère que, dans un contexte à ressources plus limitées, le numérique peut occuper une place centrale dans les représentations et les pratiques d'apprentissage. Les niveaux élevés de compétences numériques disciplinaires auto-déclarée et de valeur accordée au numérique observés à l'UNILU indiquent que le dispositif peut être perçu comme un levier essentiel d'accès aux savoirs. Cette centralité renvoie moins à une efficacité intrinsèque des dispositifs qu'à leur inscription dans un environnement où les ressources pédagogiques alternatives sont plus contraintes.

Ces constats convergent avec les recherches menées dans les contextes à ressources limitées, qui montrent que l'introduction de technologies éducatives ne garantit pas en soi une amélioration des apprentissages (Rodriguez-Segura, 2021). Les dispositifs les plus efficaces sont ceux qui associent le numérique à une structuration pédagogique explicite et à un ancrage institutionnel solide. Le modèle ETADC proposé par Sabiteka et al. (2025) souligne d'ailleurs que l'adoption durable des technologies éducatives repose sur l'interaction entre contexte institutionnel, pratiques pédagogiques et acteurs éducatifs.

Cette analyse conduit à remettre en question toute logique de transposition directe de dispositifs numériques conçus dans des contextes fortement dotés vers des environnements soumis à des contraintes structurelles importantes. Elle invite à concevoir l'innovation

pédagogique non comme un simple transfert technologique, mais comme un processus institutionnel situé, nécessitant une adaptation fine aux contextes locaux.

Ces résultats convergent pour montrer que la dimension structurelle constitue un niveau fondamental de régulation des effets du numérique en anatomie humaine. Elle définit les conditions de possibilité des usages, oriente les formes d'appropriation et configure les dynamiques d'apprentissage associées aux dispositifs numériques (Kirkwood & Price, 2014 ; OECD, 2023).

3 COMPETENCES NUMERIQUES DISCIPLINAIRES AUTODECLAREES ET PROFILS D'APPRENANTS EN ANATOMIE HUMAINE

Cette section analyse les effets du numérique à l'échelle individuelle, en montrant que les dispositifs numériques ne produisent pas des effets homogènes sur l'ensemble des apprenants. Les résultats issus des trois articles confirment empiriquement cette variabilité : à contexte pédagogique équivalent (étude préliminaire), les performances diffèrent selon les profils d'étudiants, tandis que l'article 2 montre que des étudiants exposés au même dispositif (ARanatomy) n'en tirent pas les mêmes bénéfices en fonction de leur niveau d'engagement et de leurs usages effectifs. Comme dit précédemment, nos résultats montrent que, à contexte pédagogique équivalent, les performances observées varient significativement selon les profils des étudiants et, plus spécifiquement, en fonction de leurs compétences numériques disciplinaires auto-déclarées.

Cette variabilité confirme que le numérique n'agit pas directement sur l'apprentissage : ses effets sont médiés par les ressources cognitives, stratégiques et dispositionnelles des apprenants. Dans une discipline comme l'anatomie humaine, caractérisée par une forte charge cognitive et visuo-spatiale, cette médiation apparaît particulièrement déterminante (Mayer, 2020).

3.1 Le profil de l'apprenant comme déterminant clé des effets du numérique

L'analyse conduite dans l'étude préliminaire met en évidence une variabilité marquée des effets des dispositifs numériques en fonction des profils d'apprenants, indépendamment des caractéristiques intrinsèques des outils mobilisés.

Cette variabilité est également observable dans l'article 2 (ARanatomy), où les analyses montrent que l'intensité d'usage de l'outil est associée à des variations de performance visuospatiale, sans qu'un effet direct de l'exposition au dispositif ne soit observé sur la performance académique immédiate (histologie).

Dans cette perspective, la littérature souligne que les bénéfices associés au numérique sont étroitement liés aux compétences, aux stratégies d'apprentissage et aux capacités d'autorégulation des apprenants (Hatlevik et al., 2018 ; Rienties et al., 2020). Ces médiations revêtent une importance particulière dans le champ de l'anatomie humaine, discipline caractérisée par de fortes exigences cognitives liées à la navigation spatiale, à l'articulation de multiples représentations et à la compréhension tridimensionnelle des structures anatomiques (Mayer, 2020).

L'appropriation des dispositifs numériques, telle que vue dans l'ensemble de notre travail, apparaît ainsi profondément hétérogène. Les données de l'article 2 montrent par exemple que certains étudiants adoptent des usages intensifs et diversifiés de l'outil ARanatomy, associés à de meilleures performances visuospatiales, tandis que d'autres se limitent à des usages ponctuels sans bénéfice mesurable.

Tandis que certains étudiants exploitent pleinement les potentialités offertes par les environnements tridimensionnels, d'autres se limitent à des usages plus superficiels. Cette hétérogénéité ne relève pas de simples préférences individuelles, mais renvoie à des différences structurelles en matière de compétences numériques disciplinaires auto-déclarée, lesquelles conditionnent directement la qualité de l'appropriation des outils.

3.2 Aptitudes visuospatiales et apprentissage de l'anatomie médiée par le numérique

Les aptitudes visuospatiales constituent une dimension traditionnellement considérée comme centrale dans l'apprentissage de l'anatomie humaine, en raison des exigences liées à la manipulation mentale des structures tridimensionnelles et à la navigation entre différentes représentations (Mayer, 2020). La littérature leur attribue ainsi un rôle prédictif important dans la réussite des tâches anatomiques, en particulier dans les environnements numériques (Lufler et al., 2012 ; Langlois et al., 2017).

Les résultats de cette thèse invitent toutefois à nuancer cette lecture. Dans l'étude préliminaire, les aptitudes visuospatiales initiales n'apparaissent pas comme un prédicteur significatif des performances d'apprentissage, contrairement aux compétences numériques disciplinaires. Ce résultat s'écarte partiellement des conclusions dominantes de la littérature, tout en restant cohérent avec des travaux plus récents soulignant la variabilité des effets des aptitudes spatiales selon les contextes et les dispositifs (Langlois et al., 2020).

En revanche, les analyses issues de l'article 2 (ARanatomy) montrent que l'usage des environnements numériques est associé à une amélioration des performances visuospatiales, suggérant que ces aptitudes peuvent être développées au cours de l'apprentissage, ce qui rejoint les travaux montrant que l'apprentissage de l'anatomie peut lui-même renforcer les capacités spatiales (Vorstenbosch et al., 2013). De plus, Nguyen et al. (2012) montrent que si les aptitudes visuospatiales influencent les performances initiales, leur effet peut être modulé — voire atténué — par les caractéristiques des dispositifs pédagogiques, notamment le type de visualisation et les modalités d'interaction.

Ces éléments conduisent à envisager les aptitudes visuospatiales non comme des prérequis fixes, mais comme des ressources dynamiques, susceptibles d'être modulées par les interactions avec les dispositifs numériques. Cette perspective, qui s'écarte d'une conception strictement déterministe des capacités visuospatiales, invite à reconsidérer leur rôle dans les environnements d'apprentissage en anatomie : moins comme un facteur prédictif stable que comme une compétence en développement, située et dépendante des configurations pédagogiques dans lesquelles elle s'inscrit.

3.3 Des compétences numériques génériques aux compétences numériques disciplinaires autodéclarée (ICNA)

L'une des contributions théoriques majeures de cette thèse consiste à dépasser les approches génériques des compétences numériques, largement mobilisées dans les cadres institutionnels. Des référentiels tels que DigComp ou DigCompEdu ont permis de structurer la notion de compétence numérique à l'échelle européenne (Redecker, 2017), mais leurs limites apparaissent clairement lorsqu'ils sont appliqués à des disciplines complexes comme l'anatomie humaine (Sillat et al., 2021).

Les recherches récentes en enseignement supérieur montrent que les compétences numériques sont fondamentalement situées et disciplinaires. Le cadre HeDiCom (Tondeur et al., 2023) souligne que ces compétences se construisent à l'intersection des pratiques pédagogiques, des contenus disciplinaires et des outils mobilisés. Cette perspective est particulièrement pertinente dans le champ émergent de la *digital anatomy*, où les outils numériques imposent des exigences cognitives spécifiques encore peu formalisées (Xiao et al., 2025).

Les résultats de l'article 1 (ICNA) confirment empiriquement cette perspective : les analyses montrent des différences significatives entre institutions sur l'ensemble des dimensions de l'ICNA, avec des tailles d'effet modérées à fortes, indiquant que les compétences numériques en anatomie ne sont pas distribuées de manière homogène entre les contextes. En particulier, les étudiants d'UNILU présentent des niveaux plus élevés de valeur perçue du numérique, de sentiment de compétence et d'engagement, ce qui suggère une appropriation plus marquée du numérique comme ressource d'apprentissage.

C'est dans ce contexte que s'inscrit l'originalité de la présente thèse. En concevant et en validant un indice de compétences numériques autodéclarées disciplinaires en anatomie (ICNA), ce travail répond à un manque méthodologique clairement identifié dans la littérature (Sillat et al., 2021 ; Xiao et al., 2025). Contrairement aux cadres génériques, cet indice permet de mesurer des compétences directement liées aux exigences de l'anatomie humaine.

Ce positionnement explique en grande partie pourquoi les effets du numérique observés dans cette thèse apparaissent différenciés. Les dispositifs numériques ne sollicitent pas une simple aisance technique, mais des compétences cognitives et dispositionnelles étroitement liées à la discipline, que tous les apprenants ne possèdent pas au même degré.

3.4 Compétences numériques, stratégies d'apprentissage et mécanismes d'appropriation

L'évaluation de l'ICNA met en évidence des différences significatives de compétences numériques disciplinaires autodéclarées entre les étudiants, qui apparaissent associées, dans l'étude préliminaire, à des variations de performance, en particulier différée. Ces résultats suggèrent que ces compétences interviennent dans les processus de consolidation des apprentissages, plutôt que dans les performances immédiates.

Les résultats de l'article 2 (ARAnatomy) permettent de compléter cette lecture en montrant que les usages des dispositifs numériques ne sont ni homogènes ni spontanés, mais s'inscrivent dans des configurations différenciées d'appropriation. Ces configurations se traduisent notamment par des variations importantes des perceptions d'apprentissage, du design perçu et de l'engagement entre les cohortes, telles que mesurées à partir des dimensions du modèle WBLT (Kay, 2014).

Pris ensemble, ces résultats indiquent que les compétences numériques disciplinaires auto-déclarées influencent moins directement les résultats d'apprentissage qu'elles ne conditionnent les modalités d'interaction avec les environnements numériques. Dans les environnements numériques complexes, les compétences numériques disciplinaires permettent aux apprenants de gérer plus efficacement la charge cognitive et d'exploiter les fonctionnalités avancées des outils. À l'inverse, des compétences insuffisantes peuvent conduire à des usages fragmentés ou désorientés, limitant les possibilités d'apprentissage approfondi (Akçayır & Akçayır, 2017 ; Mayer, 2020 ; Bölek et al., 2021). Dans cette perspective, l'engagement ne peut être envisagé comme un effet direct du dispositif numérique, mais comme une médiation conditionnelle, dépendante à la fois des compétences des apprenants et des caractéristiques perçues de l'environnement (notamment son ergonomie, sa lisibilité et sa cohérence pédagogique) (Fredricks et al., 2004 ; Mayer, 2020).

Sans que les stratégies d'apprentissage ne soient mesurées directement dans cette étude, ces éléments sont compatibles avec les modèles de l'apprentissage autorégulé (Zimmerman, 2002 ; Winne & Hadwin, 1998), qui postulent que la capacité à structurer son interaction avec l'environnement d'apprentissage constitue un levier central de l'engagement cognitif.

Il apparaît ainsi que les compétences numériques n'agissent pas directement sur les résultats d'apprentissage, mais qu'elles interviennent comme mécanismes d'appropriation, en conditionnant la qualité des interactions avec les dispositifs et les formes d'engagement qu'ils suscitent. Cette médiation permet d'expliquer pourquoi des dispositifs identiques peuvent produire des effets très variables, y compris au sein d'un même contexte institutionnel. Ainsi donc, les variations observées entre cohortes sur les dimensions de perception et de design suggèrent en outre que la qualité d'intégration pédagogique du dispositif constitue une condition préalable à son appropriation effective par les apprenants.

3.5 Profils d'apprenants, inégalités et contextes de formation

L'analyse des profils d'apprenants met en évidence des inégalités marquées dans le développement des compétences numériques disciplinaires en anatomie, lesquelles apparaissent étroitement liées aux contextes institutionnels de formation. Les résultats issus de la validation de l'ICNA montrent que ces profils ne se réduisent pas à des dispositions individuelles abstraites, mais renvoient à des configurations différenciées de compétences, de perceptions et de rapports au numérique, façonnées par les environnements pédagogiques.

Les comparaisons interinstitutionnelles révèlent en effet des différences statistiquement significatives sur l'ensemble des dimensions de l'ICNA. Les analyses de variance montrent des effets contextuels forts, avec des valeurs de F comprises entre 7,39 et 150,09 selon les dimensions, toutes significatives ($p < .01$). Les tailles d'effet observées entre les institutions belges et la RDC sont modérées à très élevées ($0,49 \leq d \leq 1,27$), et atteignent même une ampleur très forte pour la dimension « positivité et sentiment d'efficacité académique » ($d = 1,87$). Ces résultats indiquent que les profils d'apprenants, mesurés à partir de données autodéclarées (ICNA), varient substantiellement selon les contextes de formation, confirmant que les compétences numériques disciplinaires ne sont pas distribuées de manière homogène entre les étudiants.

Les étudiants de l'UNILU présentent ainsi des scores moyens significativement plus élevés sur l'ensemble des dimensions de l'ICNA, notamment en ce qui concerne la valeur perçue du numérique pour l'apprentissage de l'anatomie ($M = 4,34$ contre $\approx 3,22$ dans les cohortes belges) et l'usage institutionnel des technologies numériques ($M = 3,63$ contre $2,26-2,58$). Ces écarts

suggèrent que, dans des contextes où l'accès aux ressources pédagogiques est plus contraint, le numérique peut être investi comme un levier central d'accès aux savoirs et de structuration des apprentissages, renforçant à la fois l'engagement et le sentiment de compétence des étudiants (Rodriguez-Segura, 2021 ; OECD, 2023).

La littérature souligne que le développement des compétences numériques est fortement dépendant de l'intégration explicite des outils numériques dans les dispositifs pédagogiques et évaluatifs, ainsi que de leur reconnaissance institutionnelle comme ressources légitimes d'apprentissage (Kirschner & De Bruyckere, 2017 ; Tondeur et al., 2023). Les résultats de cette thèse invitent ainsi à dépasser une lecture déficitaire des profils étudiants, qui attribuerait les différences observées à des manques individuels, pour adopter une approche systémique attentive aux conditions institutionnelles et pédagogiques dans lesquelles ces compétences se construisent.

Ces inégalités de profils se répercutent directement sur les possibilités d'appropriation des dispositifs numériques et, in fine, sur les opportunités d'apprentissage offertes aux étudiants. Elles confirment que l'accès aux outils numériques ne garantit pas l'apprentissage en soi, et que les compétences numériques disciplinaires — telles que mesurées par l'ICNA — constituent un médiateur central entre dispositifs pédagogiques et effets observés sur l'engagement et les performances.

4 REPENSER LA NOTION DE PERFORMANCE EN ANATOMIE MEDIÉE PAR LE NUMÉRIQUE

Les résultats de cette thèse remettent en question l'hypothèse selon laquelle l'intégration d'outils numériques dans l'enseignement de l'anatomie conduit à une amélioration immédiate des performances académiques. Dans l'ensemble des études, aucune différence significative n'a été observée sur les performances à court terme entre les différentes modalités pédagogiques, incluant les environnements virtuels versus haptiques ainsi que les conditions actives versus passives. De même, l'utilisation d'ARanatomy n'a pas entraîné de gains significatifs en performance disciplinaire en histologie (57,8 % vs 60,0 %).

Ces résultats s'inscrivent dans la continuité des travaux classiques sur le non-déterminisme technologique (Clark, 1983 ; Kozma, 1994), mais ils en proposent ici une lecture actualisée, située empiriquement dans des contextes pédagogiques contrastés, montrant que les technologies éducatives n'exercent pas d'effet intrinsèque sur les apprentissages, mais que leur impact dépend des conditions de leur intégration pédagogique, des usages effectifs et des profils d'apprenants.

Pris dans leur ensemble, ces résultats invitent à déplacer la focale analytique : la performance ne peut plus être envisagée comme un simple effet direct des dispositifs, mais comme le produit d'un système d'interactions dynamiques entre contexte, apprenants et usages, en cohérence avec le modèle conceptuel proposé dans cette thèse. Cette interprétation est renforcée par les résultats de l'étude sur l'ICNA, qui mettent en évidence une variabilité significative des compétences numériques auto-déclarées selon les contextes.

4.1 Absence d'amélioration systématique de la performance académique immédiate

Deux de nos études convergent pour montrer que les dispositifs numériques ne produisent pas de gains académiques immédiats de manière systématique. Ni la modalité pédagogique, ni l'exposition à la réalité augmentée n'ont significativement influencé les performances à court terme. Au niveau certificatif, les taux de réussite varient de manière descriptive entre groupes (36,62 % à 61,90 %), sans différence statistiquement significative ($F(3,431) = .191$; $p = .902$).

Ces résultats sont cohérents avec des synthèses récentes rapportant des effets limités ou inconsistants des technologies immersives sur les performances académiques à court terme (Bölek et al., 2021 ; Telecan et al., 2025). Ils confirment également que l'impact des technologies éducatives dépend davantage de leur alignement pédagogique et de l'engagement des apprenants que de leurs caractéristiques techniques intrinsèques (Mayer, 2020). La robustesse de ces observations, fondées sur des échantillons importants et des contextes variés, en renforce la validité externe.

Toutefois, au-delà de ce constat, ces résultats soulignent une limite plus fondamentale : la performance académique immédiate constitue un indicateur partiel, voire réducteur, des apprentissages en contexte numérique. Elle apparaît fortement dépendante de variables médiatrices telles que l'alignement des tâches, le contexte pédagogique ou encore les ressources des apprenants, souvent peu prises en compte dans les comparaisons intergroupes.

4.2 Des effets différenciés selon le type de compétences évaluées

Si les indicateurs globaux de performance restent inchangés dans l'ensemble, des analyses plus fines révèlent des effets différenciés selon les types de compétences évaluées. En particulier, les conditions virtuelles — notamment en modalité active — sont associées à une amélioration des performances dans les tâches d'identification anatomique, tandis qu'aucune différence significative n'est observée pour les mesures visuospatiales immédiates.

A l'inverse, l'utilisation d'ARAnatomy est associée à une amélioration significative des performances visuospatiales chez les utilisateurs (41,4 % vs 31,7 % ; $p < .05$), en l'absence d'effet sur les connaissances disciplinaires. Par ailleurs, ces performances sont positivement corrélées à l'intensité d'usage, avec des associations significatives entre le score post-test et le nombre de jours actifs ($r = .30$) ainsi que le nombre de vues explorées ($r = .29$).

Ces résultats mettent en évidence un principe central : les effets du numérique ne sont ni globaux ni homogènes, mais spécifiques aux types de compétences mobilisées. Leur impact apparaît aligné avec leurs affordances cognitives, notamment la manipulation spatiale, l'exploration tridimensionnelle et l'intégration de représentations multiples.

Cette interprétation est cohérente avec la littérature, qui montre que les environnements immersifs soutiennent particulièrement la cognition spatiale, tout en ayant un effet plus limité sur l'acquisition de connaissances déclaratives à court terme (Mayer, 2020 ; Bogomolova et al., 2021).

4.3 L'alignement entre dispositifs numériques et modalités d'évaluation

Une autre contribution majeure de cette thèse réside dans la mise en évidence du rôle déterminant de l'alignement entre les dispositifs numériques et les modalités d'évaluation.

Lorsque les évaluations portent sur des compétences qui correspondent aux usages permis par les outils (telles que le raisonnement spatial ou l'identification anatomique) des effets significatifs émergent. A l'inverse, lorsque les évaluations reposent sur des formats traditionnels, peu sensibles à ces processus cognitifs, les effets des dispositifs numériques demeurent indétectables.

Ces résultats suggèrent que l'absence d'effet observé dans certaines conditions ne traduit pas nécessairement une absence d'apprentissage, mais peut relever d'un défaut d'alignement entre ce qui est appris et ce qui est mesuré.

Ces observations rejoignent les travaux de Kirkwood et Price (2014), selon lesquels l'efficacité des technologies éducatives dépend avant tout de leur articulation avec les objectifs pédagogiques et les modalités d'évaluation.

4.4 Vers une conception élargie et médiée de la performance

Dans leur ensemble, les résultats soutiennent une reconceptualisation de la performance académique comme un construit médié et multidimensionnel. Les performances observées ne sont pas déterminées par la seule modalité pédagogique, mais résultent d'une combinaison de facteurs contextuels et individuels. En particulier, la compétence numérique auto-déclarée apparaît plus fortement associée à la performance différée ($r = .41$) que l'aptitude visuospatiale ($r = .23$), soulignant son rôle central comme facteur facilitateur dans les environnements d'apprentissage numériques.

Par ailleurs, la performance est étroitement liée aux modalités d'engagement, l'intensité d'usage constituant un prédicteur significatif des apprentissages. Cette observation s'inscrit dans la continuité des modèles de l'engagement étudiant, qui soulignent le rôle de la participation active dans les processus d'apprentissage (Fredricks et al., 2004).

Enfin, les résultats de l'article sur l'ICNA montrent que les apprenants abordent les environnements numériques avec des ressources inégalement distribuées, incluant la motivation, le sentiment d'efficacité personnelle et la littératie numérique critique.

Ces résultats conduisent à proposer une redéfinition de la performance en anatomie médiée par le numérique : non plus comme un indicateur ponctuel et unidimensionnel, mais comme un processus dynamique, distribué et contextuellement situé, intégrant des dimensions cognitives, visuospatiales, motivationnelles et interactionnelles.

Dès lors, la performance ne constitue plus uniquement un résultat, mais devient un indicateur des conditions dans lesquelles l'apprentissage est rendu possible, révélant ainsi les interactions entre les dimensions structurelle, individuelle et processuelle du modèle conceptuel.

5 L'USAGE REEL : VARIABLE CLE, MAIS ENCORE PARTIELLEMENT INVISIBLE

Cette section vise à analyser le niveau processuel des effets du numérique en anatomie humaine, en se concentrant sur les usages effectifs des dispositifs numériques et sur les formes d'engagement qu'ils suscitent. Les résultats de l'article sur ARanatomy montrent que les effets observés sur l'apprentissage ne peuvent être expliqués ni par les seules intentions pédagogiques, ni par la simple présence d'un outil numérique, mais doivent être compris à partir des formes concrètes d'appropriation réalisées par les étudiants.

Cette approche s'inscrit directement dans les travaux de notre équipe, qui ont montré que les environnements numériques instrumentés, tels que la microscopie virtuelle Cytomine®, permettent de passer d'une analyse des résultats d'apprentissage à une analyse fine des comportements d'apprentissage (Allyson, 2024).

5.1 Des intentions pédagogiques aux usages effectifs des dispositifs numériques

Les résultats mettent en évidence un décalage récurrent entre les intentions pédagogiques et les usages effectivement réalisés. Même lorsque les outils sont conçus selon des principes pédagogiques explicites, leurs modalités d'utilisation restent largement dépendantes des logiques d'action des apprenants (Cuban, 2001 ; Selwyn, 2017).

Dans la cohorte 5 de l'article 2 (ARanatomy), les traces d'usage montrent une forte variabilité : certains étudiants n'ont réalisé que quelques interactions, tandis que d'autres ont exploré intensivement les contenus, avec jusqu'à 1400 interactions pour les objets les plus consultés.

Les analyses instrumentées montrent que les « High Users » utilisent l'application sur un plus grand nombre de jours distincts, signe d'une régularité d'usage accrue ($r = 0.30$; $p < 0.05$) et ont un volume d'exploration plus important ($r = 0.29$; $p < 0.05$).

5.2 Hétérogénéité des usages et variabilité des effets d'apprentissage

L'analyse des traces d'interaction révèle une forte hétérogénéité des usages, tant en fréquence qu'en durée ou en modes d'interaction.

Les travaux menés sur Cytomine® montrent que certains comportements spécifiques — tels que le respect des parcours annotés, l'exploration progressive des structures ou la consultation des annotations dans l'ordre pédagogique — sont particulièrement prédictifs de la réussite académique (Fries, 2024).

Dans la cohorte 4 (UNILU, instrumentation partielle), les utilisateurs obtiennent un score post-test moyen de 41,4 %, contre 31,7 % pour les non-utilisateurs ($p < 0.05$). Ce résultat met en évidence une association entre l'usage de l'outil et la performance visuospatiale, suggérant que les environnements numériques peuvent soutenir certaines dimensions spécifiques de l'apprentissage, en particulier celles liées à la manipulation et à l'exploration spatiale.

Cependant, comme déjà observé dans les analyses du laboratoire, ces différences reflètent davantage des profils d'engagement que des effets directs du dispositif : les étudiants les plus actifs adoptent aussi des stratégies d'apprentissage plus efficaces.

5.3 Dynamiques motivationnelles et structuration des usages

Les résultats issus des cohortes instrumentées permettent de montrer que l'appropriation des dispositifs numériques dépend aussi de variables motivationnelles, notamment le sentiment de compétence, l'autonomie perçue et l'engagement de l'apprenant. Ces dimensions influencent la persistance, l'implication et l'usage effectif des outils dans les contextes d'apprentissage (Ryan & Deci, 2000 ; Fredricks et al., 2004).

Il en ressort que l'intensité d'utilisation des environnements numériques est significativement associée aux profils motivationnels des apprenants. En particulier, la motivation intrinsèque et les émotions positives sont positivement corrélées à la fréquence et à la régularité des usages, tandis que l'amotivation est associée à une moindre utilisation des dispositifs. Par ailleurs, dans la cohorte 5 (HEPL, instrumentation complète), le temps passé en mode réalité augmentée apparaît corrélé à la motivation extrinsèque et aux émotions positives.

Ainsi donc, les usages effectifs ne relèvent pas uniquement de l'accessibilité des outils ou des intentions pédagogiques, mais s'inscrivent dans des dynamiques motivationnelles différenciées, qui orientent les modalités d'interaction avec les dispositifs numériques.

En revanche, les comparaisons entre utilisateurs et non-utilisateurs ne mettent pas en évidence de différences significatives en termes d'engagement perçu, tel que mesuré par le WBLT (Kay, 2014). Cette absence d'effet suggère que l'engagement déclaratif ne constitue pas un indicateur suffisant pour rendre compte des processus d'appropriation des environnements numériques.

Vu sous cet angle, la motivation intervient moins comme un déterminant direct des apprentissages que comme un facteur influençant l'intensité et la qualité des usages. Les effets observés sur la performance semblent donc davantage résulter des modalités d'interaction avec le dispositif que de la motivation elle-même.

5.4 Mesures instrumentées des usages : rendre visible l'invisible ?

Les résultats issus des versions instrumentées d'ARanatomy mettent en évidence le potentiel des approches de *learning analytics* pour objectiver les usages réels des dispositifs numériques. La collecte de traces fines (sessions, jours d'activité, objets explorés, durée d'interaction, navigation entre niveaux anatomiques et histologiques) permet d'accéder à des dimensions de l'apprentissage habituellement invisibles dans les approches déclaratives.

Les analyses montrent que certaines variables d'usage — notamment le nombre de jours actifs et le volume d'exploration — sont associées aux performances visuospatiales, suggérant que l'intensité et la régularité de l'activité constituent des indicateurs pertinents des processus d'apprentissage en environnement numérique. Ces résultats confirment l'intérêt des données instrumentées pour dépasser les limites des mesures fondées uniquement sur les performances ou les perceptions.

Cependant, ces indicateurs restent principalement quantitatifs et comportementaux. Ils décrivent l'activité observable, sans permettre d'accéder directement aux processus cognitifs sous-jacents. Ainsi, un volume élevé d'interactions ne garantit pas nécessairement une compréhension approfondie des structures anatomiques.

Les résultats confirment cette limite : si certaines variables d'usage sont associées à des variations de performance, les analyses classiques ne permettent pas d'établir de relation

causale directe, notamment en raison de l'absence d'évolution significative dans certaines mesures pré/post.

Toutefois, cette limite doit être nuancée à la lumière d'approches analytiques plus avancées. Les travaux menés à partir de plateformes instrumentées telles que Cytomine, combinés à des méthodes de *machine learning*, montrent qu'il est possible d'extraire des signaux prédictifs robustes à partir des traces d'interaction (Fries, 2024). Ces approches permettent d'identifier des profils d'apprenants, de modéliser des trajectoires d'apprentissage et d'anticiper certains résultats.

Il faudra dès lors retenir que l'enjeu ne réside plus uniquement dans la quantification de l'usage, mais dans sa modélisation fine, intégrant la temporalité et les patterns d'interaction. L'usage apparaît ainsi comme une variable centrale mais partiellement invisible, dont le potentiel explicatif dépend étroitement des méthodes mobilisées pour l'analyser.

6 LIMITES ET PERSPECTIVES

6.1 Limites de cette recherche

Sur le plan méthodologique, plusieurs précautions ont été mises en œuvre afin de renforcer la robustesse des résultats obtenus. Les études multicentriques reposaient notamment sur des dispositifs pédagogiques standardisés, des objectifs d'apprentissage communs, des protocoles expérimentaux harmonisés et des analyses statistiques adaptées à la complexité des données recueillies. Néanmoins, comme dans toute recherche conduite en contexte authentique d'enseignement, certaines variations liées aux spécificités institutionnelles n'ont pu être totalement contrôlées, limitant l'isolement d'effets strictement causaux.

Les contextes étudiés, principalement la Belgique et la République Démocratique du Congo, offrent une diversité pertinente, mais ne couvrent pas l'ensemble des réalités pédagogiques. Les résultats ne peuvent donc être généralisés à d'autres institutions disposant d'infrastructures, de cultures pédagogiques ou de niveaux de maturité numérique différents.

Enfin, le modèle proposé pourrait être enrichi par l'intégration de dimensions sociales, émotionnelles ou collaboratives.

6.2 Perspectives

A partir de ces constats, plusieurs perspectives de recherche peuvent prolonger et approfondir les apports de cette thèse.

Une première piste consiste à étendre les études à d'autres contextes institutionnels, notamment en Asie, en Amérique latine et au Moyen-Orient, afin de vérifier la robustesse du modèle interactionniste dans des environnements pédagogiques différents. L'analyse des politiques institutionnelles, des cultures pédagogiques et des modèles curriculaires permettrait également de mieux comprendre les conditions d'intégration du numérique.

L'ICNA pourrait encore être enrichi par de nouvelles dimensions comme l'autorégulation numérique, le raisonnement spatial dynamique ou les compétences épistémologiques, et adapté à d'autres disciplines visuo-spatiales comme la radiologie ou la chirurgie.

L'analyse des usages pourrait aussi être approfondie grâce aux learning analytics avancés. L'intégration d'approches de machine learning permettrait de mieux identifier les trajectoires

d'apprentissage, les profils d'usage et les dynamiques d'engagement. Le croisement des traces numériques avec des données physiologiques, comme l'eye-tracking ou la biométrie cognitive, ainsi qu'avec des analyses qualitatives, offrirait une compréhension plus complète des processus d'apprentissage.

Les technologies émergentes représentent également un champ de recherche prometteur. L'étude de la réalité virtuelle immersive, de la réalité mixte, des simulateurs haptiques avancés et des intelligences artificielles génératives permettrait d'explorer de nouvelles formes d'apprentissage, y compris dans des contextes à ressources limitées.

Enfin, le développement de modèles pédagogiques contextualisés reste essentiel. Concevoir des dispositifs numériques adaptés aux réalités matérielles, culturelles et institutionnelles locales, ainsi que tester des modèles hybrides combinant ressources numériques, apprentissage collaboratif et activités pratiques, pourrait favoriser une intégration plus pertinente et plus durable du numérique en anatomie humaine.

7 CONCLUSION : VERS UNE COMPREHENSION INTERACTIONNISTE DES EFFETS DU NUMERIQUE EN ANATOMIE HUMAINE ?

Cette thèse propose une compréhension renouvelée des effets du numérique dans l'apprentissage de l'anatomie humaine, en dépassant les approches technocentrées pour inscrire l'analyse dans une perspective interactionniste. Les résultats montrent que les technologies ne possèdent pas d'efficacité pédagogique intrinsèque et que leurs effets dépendent étroitement de l'articulation entre trois niveaux : les contextes institutionnels, les compétences numériques disciplinaires des apprenants et les usages effectifs des dispositifs.

L'analyse structurelle met en évidence que les environnements pédagogiques et institutionnels configurent les opportunités d'usage et conditionnent la manière dont les dispositifs numériques peuvent être intégrés. La dimension individuelle montre que les compétences numériques disciplinaires constituent une médiation essentielle entre les outils et les apprentissages. Enfin, la dimension processuelle révèle que les usages réels, l'engagement et les formes d'appropriation déterminent la transformation — ou non — des ressources disponibles en apprentissages effectifs.

L'ensemble de ces résultats conduit à proposer un modèle interactionniste empirique des effets du numérique en anatomie humaine, capable de dépasser les lectures causales simplistes et d'offrir un cadre analytique transférable à d'autres disciplines complexes et visuo-spatiales. Ce modèle repositionne le numérique non comme une solution universelle, mais comme un levier conditionnel dont l'efficacité dépend de son inscription dans des contextes cohérents, du développement intentionnel des compétences numériques disciplinaires et de l'accompagnement des usages.

Au-delà du champ de l'anatomie, cette thèse invite à repenser les effets du numérique dans l'enseignement supérieur selon une approche située et interactionniste. Elle souligne l'importance de contextualiser les dispositifs pédagogiques et ouvre des perspectives de recherche autour du développement de learning analytics plus fines et d'environnements numériques mieux adaptés aux réalités institutionnelles et aux profils des apprenants.

BIBLIOGRAPHIE

1. Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, 20, 1–11. <https://doi.org/10.1016/j.edurev.2016.11.002>
2. Al-Rubaie, A. (2024). From cadavers to codes: The evolution of anatomy education through digital technologies. *Medical Science Educator*. Advance online publication. <https://doi.org/10.1007/s40670-024-02268-6> (ResearchGate)
3. Anderson, L. W., & Krathwohl, D. R. (Eds.). (2001). A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives. New York, NY: Longman.
4. Arráez-Aybar, L. A. (2025). Evolving anatomy education: Bridging dissection, traditional methods, and technological innovation for clinical excellence. *Anatomia*, 4(2), 9. <https://doi.org/10.3390/anatomia4020009> (mdpi.com)
5. Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, 6(4), 355–385. <https://doi.org/10.1162/pres.1997.6.4.355>
6. Barron, B. (2006). Interest and self-sustained learning as catalysts of development: A learning ecology perspective. *Human Development*, 49(4), 193–224. <https://doi.org/10.1159/000094368>
7. Biggs, J. (1996). Enhancing teaching through constructive alignment. *Higher Education*, 32(3), 347–364. <https://doi.org/10.1007/BF00138871>
8. Bleakley, A. (2010). Blunting Occam's razor: Aligning medical education with studies of complexity. *Journal of Evaluation in Clinical Practice*, 16(4), 849–855. <https://doi.org/10.1111/j.1365-2753.2010.01498.x>
9. Bogomolova, K., Sam, A. H., Misky, A. T., Gupte, C. M., Strutton, P. H., Hurkxkens, T. J., & Hierck, B. P. (2021). Development of a virtual three-dimensional assessment scenario for anatomical education. *Anatomical Sciences Education*, 14(3), 385–393. <https://doi.org/10.1002/ase.2055>
10. Bohl, M. A., & Gest, T. R. (2011). Resident perceptions of anatomy education: A survey of medical school alumni from two different anatomy curricula and multiple medical specialties. *Anatomical Sciences Education*, 4(3), 126–131. <https://doi.org/10.1002/ase.207>
11. Bölek, K. A., De Jong, G., & Henssen, D. (2021). The effectiveness of the use of augmented reality in anatomy education: A systematic review and meta-analysis. *Scientific Reports*, 11(1), 15292. <https://doi.org/10.1038/s41598-021-94721-4>
12. Chang Chan, A. Y. C., van Leeuwen, M., Custers, E., Bleys, R., & Ten Cate, O. (2025). Anatomy education in low-resourced countries: What are challenges and effective and affordable educational strategies? A qualitative study. *Medical teacher*, 47(5), 883–893. <https://doi.org/10.1080/0142159X.2024.2383373>
13. Chang Chan, A. Y., Stapper, C. P. M., Bleys, R. L. A. W., van Leeuwen, M., & Ten Cate, O. (2022). Are we facing the end of gross anatomy teaching as we have known it for centuries? *Advances in Medical Education and Practice*, 13, 1243–1250. <https://doi.org/10.2147/AMEP.S378149>
14. Chatha, W. A. (2024). From scalpel to simulation: Reviewing the future of cadaveric dissection in the upcoming era of virtual and augmented reality and artificial intelligence. *Cureus*, 16(10), e71578. <https://doi.org/10.7759/cureus.71578>

15. Cheng, C., Yu, S., & Li, G. (2026). The impact of digital tools on learning strategies and academic performance in human anatomy. In *Proceedings of SPIE 14018, International Conference on Mechanical, Engineering, and Interaction Design (ICMEID 2025) (140186L)*. SPIE. <https://doi.org/10.1117/12.3088904>
16. Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist*, 49(4), 219–243. <https://doi.org/10.1080/00461520.2014.965823>
17. Clark, R. E. (1983). Reconsidering research on learning from media. *Review of Educational Research*, 53(4), 445–459. <https://doi.org/10.3102/00346543053004445>
18. Clark, R. E. (1994). Media will never influence learning. *Educational Technology Research and Development*, 42(2), 21–29. <https://doi.org/10.1007/BF022990>
19. Cook, D. A., Brydges, R., Ginsburg, S., & Hatala, R. (2015). A contemporary approach to validity arguments: A practical guide to Kane’s framework. *Medical Education*, 49(6), 560–575. <https://doi.org/10.1111/medu.12678>
20. Cook, D. A., Levinson, A. J., Garside, S., Dupras, D. M., Erwin, P. J., & Montori, V. M. (2008). Internet-based learning in the health professions: A meta-analysis. *JAMA*, 300(10), 1181–1196. <https://doi.org/10.1001/jama.300.10.1181>
21. Cuban, L. (2001). *Oversold and underused: Computers in the classroom*
22. Darius, B., Auverdin, S., Jonathan, I. D., Pacifique, N., Chifra, I. A., Fabrice, N., Moise, T., Dieudonne, N., & Salomon, I. (2025). The role of anatomy education in strengthening healthcare in Rwanda. *Annals of Medicine and Surgery*, 87(6), 3537–3541. <https://doi.org/10.1097/MS9.00000000000003287>
23. Dede, C. (2014). The role of digital technologies in deeper learning. In J. A. Bellanca & E. C. Brandt (Eds.), *Deeper learning: Beyond 21st century skills* (pp. 59–73). Solution Tree Press.
24. Djembi, Y. R., Abiome, R., Mikiéla, A., Mba Mba, C., Koussou, R., Ndjota, N., Bayonne Manou, L. S., Boumas, N., & Ondo Ndong, F. (2026). Teaching anatomy in the Bantu context: Traditions, cultural issues and educational perspectives in Gabon. *Morphologie*, 110(369), 101104. <https://doi.org/10.1016/j.morpho.2025.101104>
25. Ellaway, R. H., & Bates, J. (2015). Exploring patterns and pattern languages of medical education. *Medical Education*, 49(12), 1189–1196. <https://doi.org/10.1111/medu.12836>
26. Engeström, Y. (2001). Expansive learning at work: Toward an activity theoretical reconceptualization. *Journal of Education and Work*, 14(1), 133–156. <https://doi.org/10.1080/13639080020028747>
27. Fevry, J., Fotsing, S., Merghem, M., Roberge, A., Ramdani, R., Fillion, I., Domecq, M. C., & Jalali, A. (2026). Profile of anatomy teachers of students in healthcare professions: A scoping review. *BMC Medical Education*, 26(1), 440. <https://doi.org/10.1186/s12909-026-08721-x>
28. Florida Center for Instructional Technology. (2005). Technology Integration Matrix. *University of South Florida*. <https://fcit.usf.edu/matrix/>
29. Foiret, J. R., & Volschenk, M. (2024). Exploring the use of a digital anatomy learning platform in a second-year medical student cohort. *Anatomical Sciences Education*, 17(3), 591–604. <https://doi.org/10.1002/ase.2384>

30. Fredricks, J. A., Blumenfeld, P. C., & Paris, A. H. (2004). School engagement: Potential of the concept, state of the evidence. *Review of Educational Research*, 74(1), 59–109. <https://doi.org/10.3102/00346543074001059>
31. Fries, A., Pirotte, M., Vanhee, L., Bonnet, P., Quatresooz, P., Debruyne, C., Marée, R., & Defaweux, V. (2024). Validating instructional design and predicting student performance in histology education: Using machine learning via virtual microscopy. *Anatomical Sciences Education*, 17(5), 984–997. <https://doi.org/10.1002/ase.2346>
32. Gabriel, A. G., & Chia, S. L. (2025). High price of perfection that is anatomy: Why studying and teaching the human body is a financial muscle. *Journal of Innovations in Medical Research*, 4(2), 84–90. <https://doi.org/10.63593/JIMR.2788-7022.2025.04.010>
33. Gašević, D., Dawson, S., & Siemens, G. (2015). Let's not forget: Learning analytics are about learning. *TechTrends*, 59(1), 64–71. <https://doi.org/10.1007/s11528-014-0822-x>
34. Goldman, E. (2010). Building a low-cost gross anatomy laboratory: A big step for a small university. *Anatomical Sciences Education*, 3: 195–201. <https://doi.org/10.1002/ase.160>
35. Goodyear, P., Carvalho, L., & Dohn, N. B. (2014). Design for networked learning: Framing relations between participants' activities and the physical setting. In *Proceedings of the 9th International Conference on Networked Learning* (pp. 137–144). <https://doi.org/10.54337/nlc.v9.8980>
36. Graham, C. R. (2006). Blended learning systems: Definition, current trends, and future directions. In C. J. Bonk & C. R. Graham (Eds.), *Handbook of blended learning: Global perspectives, local designs* (pp. 3–21). Pfeiffer.
37. Greeno, J. G. (1998). The situativity of knowing, learning, and research. *American Psychologist*, 53(1), 5–26. <https://doi.org/10.1037/0003-066X.53.1.5>
38. Gros, B. (2016). The design of smart educational environments. *Smart Learning Environments*, 3(1), Article 15. <https://doi.org/10.1186/s40561-016-0039-x>
39. Habicht, J. L., Kiessling, C., & Winkelmann, A. (2018). Bodies for anatomy education in medical schools: An overview of the sources of cadavers worldwide. *Academic Medicine*, 93(9), 1293–1300. <https://doi.org/10.1097/ACM.0000000000002227>
40. Hatlevik, I. K. R., & Hatlevik, O. E. (2018). Examining the relationship between teachers' ICT self-efficacy for educational purposes, collegial collaboration, lack of facilitation and the use of ICT in teaching practice. *Frontiers in Psychology*, 9, 935. <https://doi.org/10.3389/fpsyg.2018.00935>
41. Heinich, R., Molenda, M., Russell, J. D., & Smaldino, S. E. (2001). *Instructional media and technologies for learning* (7th ed.). Prentice Hall
42. Hoffman, H., & Vu, D. (1997). Virtual reality: Teaching tool of the twenty-first century? *Academic Medicine*, 72(12), 1076–1081. <https://doi.org/10.1097/00001888-199712000-00018>
43. International Federation of Associations of Anatomists. (2014). Recommendations of good practice for the donation and study of human bodies and tissues for anatomical examination. *Plexus (Newsletter of the International Federation of Associations of Anatomists)*, August 2014.
44. Issenberg, S. B., McGaghie, W. C., Petrusa, E. R., Gordon, D. L., & Scalese, R. J. (2005). Features and uses of high-fidelity medical simulations that lead to effective learning: A BEME systematic review. *Medical Teacher*, 27(1), 10–28. <https://doi.org/10.1080/01421590500046924>

45. Iwanaga, J., Loukas, M., Dumont, A. S., & Tubbs, R. S. (2021). A review of anatomy education during and after the COVID-19 pandemic: Revisiting traditional and modern methods to achieve future innovation. *Clinical anatomy (New York, N.Y.)*, 34(1), 108–114. <https://doi.org/10.1002/ca.23655>
46. Jones, D. G. (2024). Do religious and cultural considerations militate against body donation? An overview and a Christian perspective. *Anatomical Sciences Education*, 17, 1586–1595. <https://doi.org/10.1002/ase.2425>
47. Kay, R. H. (2014). Exploring the use of web-based learning tools in secondary school classrooms. *Interactive Learning Environments*, 22(1), 67–83. <https://doi.org/10.1080/10494820.2011.641675>
48. Kimmons, R., Draper, D., & Backman, J. (2022). PICRAT: The PICRAT technology integration model. In *EdTechnica: The open encyclopedia of educational technology* (pp. 225–233). *EdTech Books*. <https://doi.org/10.59668/371.5895>
49. Kirkwood, A., & Price, L. (2014). Technology-enhanced learning and teaching in higher education: What is “enhanced” and how do we know? A critical literature review. *Learning, Media and Technology*, 39(1), 6–36. <https://doi.org/10.1080/17439884.2013.770404>
50. Kirschner, P. A., & De Bruyckere, P. (2017). The myths of the digital native and the multitasker. *Teaching and Teacher Education*, 67, 135–142. <https://doi.org/10.1016/j.tate.2017.06.001>
51. Kozma, R. B. (1994). Will media influence learning? Reframing the debate. *Educational Technology Research and Development*, 42(2), 7–19. <https://doi.org/10.1007/BF02299087>
52. Langlois, J., Bellemare, C., Toulouse, J., & Wells, G. A. (2017). Spatial abilities and anatomy knowledge assessment: A systematic review. *Anatomical Sciences Education*, 10(3), 235–241. <https://doi.org/10.1002/ase.1655>
53. Langlois, J., Bellemare, C., Toulouse, J., & Wells, G. A. (2020). Spatial abilities training in anatomy education: A systematic review. *Anatomical Sciences Education*, 13(1), 71–79. <https://doi.org/10.1002/ase.1873>
54. Laurillard, D. (2012). Teaching as a design science: Building pedagogical patterns for learning and technology. *Routledge*. <https://doi.org/10.4324/9780203125083>
55. Leclercq, D. (2008). *Radiographier les Concordances O-M-E-R d'un cours ou d'un curriculum. Chapitre 5 du cours de "Conception et évaluation de curriculum"*. (ULiège - Université de Liège, PEDAO053-1 Construction de curriculums et technologie de l'éducation et de la formation, 30h Th, 30h Pr).
56. Longhurst, G. J., Stone, D. M., Dulohery, K., Scully, D., Campbell, T., & Smith, C. F. (2022). Strength, weakness, opportunity, threat (SWOT) analysis of the adaptations to anatomical education in the United States during the COVID-19 pandemic. *BMC Medical Education*, 22, Article 394. <https://doi.org/10.1186/s12909-022-03405-8>
57. Lufler, R. S., Zumwalt, A. C., Romney, C. A., & Hoagland, T. M. (2012). Effect of visual-spatial ability on medical students' performance in a gross anatomy course. *Anatomical Sciences Education*, 5(1), 3–9. <https://doi.org/10.1002/ase.264>
58. Luursema, J.-M., Verwey, W. B., Kommers, P. A. M., & Annema, J.-H. (2008). The role of stereopsis in virtual anatomical learning. *Interacting with Computers*, 20(4–5), 455–460. <https://doi.org/10.1016/j.intcom.2008.04.003>
59. Lythreath, S., Singh, S. K., & El-Kassar, A.-N. (2022). The digital divide: A review and future research agenda. *Technological Forecasting and Social Change*, 175, 121359. <https://doi.org/10.1016/j.techfore.2021.121359>

60. Mayer, R. E. (2020). *Multimedia learning* (3rd ed.). Cambridge University Press. <https://doi.org/10.1017/9781316941355>
61. McMenamin, P. G., Costello, L. F., Quayle, M. R., Bertram, J. F., Kaka, A., Tefuarani, N., & Adams, J. W. (2025). Challenges of access to cadavers in low- and middle-income countries (LMIC) for undergraduate medical teaching: A review and potential solutions in the form of 3D printed replicas. *3D Print Medicine*, 11(1), 28. <https://doi.org/10.1186/s41205-025-00277-8>
62. Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record*, 108(6), 1017–1054. <https://doi.org/10.1111/j.1467-9620.2006.00684.x>
63. Moersch, C. (1995). Levels of technology implementation (LoTi): A framework for measuring classroom technology use. *Learning and Leading with Technology*, 23(3), 40–42.
64. Moersch, C. (2002). Measures of success: Six instruments to assess teachers' use of technology. *Learning and Leading with Technology*, 30(3), 10–13, 24–28.
65. Moro, C., Birt, J., Stromberga, Z., Phelps, C., Clark, J., Glasziou, P., Scott, A. M., & Campbell, M. (2021). Virtual and augmented reality enhancements to medical and science student physiology and anatomy test performance: A systematic review and meta-analysis. *Anatomical Sciences Education*, 14(3), 368–376. <https://doi.org/10.1002/ase.2049>
66. Moxham, B., & Plaisant, O. (2005). Quel est le but de l'anatomie dans le cursus médical ? Perception des étudiants de l'importance clinique de l'anatomie. *Morphologie*, 89(287), 201–202. [https://doi.org/10.1016/S1286-0115\(05\)82559-9](https://doi.org/10.1016/S1286-0115(05)82559-9)
67. Nguyen, N., Nelson, A. J., & Wilson, T. D. (2012). Computer visualizations: Factors that influence spatial anatomy comprehension. *Anatomical Sciences Education*, 5(2), 98–108. <https://doi.org/10.1002/ase.1258>
68. Nicholson, D. T., Chalk, C., Funnell, W. R. J., & Daniel, S. J. (2006). Can virtual reality improve anatomy education? A randomised controlled study of a computer-generated three-dimensional anatomical ear model. *Medical Education*, 40(11), 1081–1087. <https://doi.org/10.1111/j.1365-2929.2006.02611.x>
69. Nieder, G. L., & Nagy, F. (2002). Analysis of medical students' use of Web-based resources for a gross anatomy and embryology course. *Clinical Anatomy*, 15(6), 409–418. <https://doi.org/10.1002/ca.10067>
70. Nokovitch, L., El Hajj, H., Deneuve, S., De Andrade, V., Gagnayre, R., & Margat, A. (2025). Visual-spatial abilities enhancement and spatial anatomy learning: A systematic review. *Medical Education*, 59(12), 1322–1332. <https://doi.org/10.1111/medu.70022>
71. OECD. (2023). OECD Digital Education Outlook 2023: Towards an Effective Digital Education Ecosystem. *OECD Publishing*. <https://doi.org/10.1787/c74f03de-en>
72. Pather, N., Blyth, P., Chapman, J. A., Dayal, M. R., Flack, N. A., Fogg, Q. A., Green, R. A., Hulme, A. K., Johnson, I. P., Meyer, A. J., Morley, J. W., Shortland, P. J., Strkalj, G., Strkalj, M., Valter, K., Webb, A. L., Woodley, S. J., & Lazarus, M. D. (2020). Forced disruption of anatomy education in Australia and New Zealand: An acute response to the COVID-19 pandemic. *Anatomical Sciences Education*, 13(3), 284–297. <https://doi.org/10.1002/ase.1968>
73. Provenzo, E. F. (1986). Review of the book Teachers and machines: The classroom use of technology since 1920, by L. Cuban. *History of Education Quarterly*, 26(4), 647–648. <https://doi.org/10.2307/369036>

74. Puentedura, R. R. (2006). Transformation, technology, and education. Retrieved from <http://hippasus.com/resources/tte/>
75. Quatresooz, P., Bonnet, P., Radermecker, M., Weatherspoon, A., Pesesse, L., Comblain, F., Vandenbosch, R., Pirotte, M., Dernier, A., Nizet, C., Walhin, N., & Defaweux, V. (2021). Travaux pratiques d'anatomie et d'histologie à distance. *Revue internationale des technologies en pédagogie universitaire*, 18(1), 184–193. <https://doi.org/10.18162/ritpu-2021-v18n1-16>
76. Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education*, 147, 103778. <https://doi.org/10.1016/j.compedu.2019.103778>
77. Redecker, C. (2017). *European framework for the digital competence of educators: DigCompEdu* (Y. Punie, Ed.). Publications Office of the European Union. <https://doi.org/10.2760/159770>
78. Richard E. Mayer (2021). *Multimedia learning* (3rd ed.). Cambridge University Press. <https://doi.org/10.1017/9781316941355>
79. Rienties, B., Brouwer, N., & Lygo-Baker, S. (2013). The effects of online professional development on higher education teachers' beliefs and intentions towards learning facilitation and technology. *Teaching and Teacher Education*, 29, 122–131. <https://doi.org/10.1016/j.tate.2012.09.002>
80. Roblyer, M. D., & Doering, A. H. (2014). Integrating educational technology into teaching (6th ed.). Pearson.
81. Rodriguez-Segura, D. (2021). EdTech in developing countries: A review of the evidence. *The World Bank Research Observer*, 37(2), 171–203. <https://doi.org/10.1093/wbro/lkab011>
82. Rogers, E. M. (2003). Diffusion of innovations (5th ed.). Free Press.
83. Ruiz, J. G., Mintzer, M. J., & Leipzig, R. M. (2006). The impact of e-learning in medical education. *Academic Medicine*, 81(3), 207–212. <https://doi.org/10.1097/00001888-200603000-00002>
84. Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist*, 55(1), 68–78. <https://doi.org/10.1037/0003-066X.55.1.68>
85. Sabiteka, M., Yu, X., & Sun, C. (2025). Toward Sustainable Education: A Contextualized Model for Educational Technology Adoption for Developing Countries. *Sustainability*, 17(8), 3592. <https://doi.org/10.3390/su17083592>
86. Sakr, A., & Abdullah, T. (2024). Virtual, augmented reality and learning analytics impact on learners, and educators: A systematic review. *Education and Information Technologies*, 29(15), 19913–19962. <https://doi.org/10.1007/s10639-024-12602-5>
87. Sbayeh, A., Qaedi Choo, M. A., Quane, K. A., Finucane, P., McGrath, D., O'Flynn, S., O'Mahony, S. M., & O'Tuathaigh, C. M. P. (2016). Relevance of anatomy to medical education and clinical practice: Perspectives of medical students, clinicians, and educators. *Perspectives on Medical Education*, 5(6), 338–346. <https://doi.org/10.1007/s40037-016-0310-4>

88. Selwyn, N. (2017). Education and technology: Key issues and debates (2nd ed.). Education and Technology: *Key Issues and Debates* London: Bloomsbury Academic. <https://doi.org/10.5040/9781474235952>
89. Siemens, G. (2013). Learning analytics: The emergence of a discipline. *American Behavioral Scientist*, 57(10), 1380–1400. <https://doi.org/10.1177/0002764213498851>
90. Sillat, L. H., Tammets, K., & Laanpere, M. (2021). Digital competence assessment methods in higher education: A systematic literature review. *Education Sciences*, 11(8), 402. <https://doi.org/10.3390/educsci11080402>
91. Telecan, T., Capraș, R.-D., Filip, G. A., Bonea, M., & Crivii, C.-B. (2025). Dissection in the 21st century: Virtual tables versus traditional methods and their influence on medical students' perception – A systematic review. *BMC Medical Education*, 25, 1332. <https://doi.org/10.1186/s12909-025-07946-6>
92. Tondeur, J., Howard, S., Van Zanten, M., Scherer, R., Siddiq, F., Valtonen, T., ... & Aesaert, K. (2023). The HeDiCom framework: Higher education teachers' digital competencies for the future. *Educational Technology Research and Development*, 71(1), 33–53. <https://doi.org/10.1007/s11423-023-10193-5>
93. Triepels, C. P. R., Smeets, C. F. A., Notten, K. J. B., Kruitwagen, R. F. P. M., Futterer, J. J., Vergeldt, T. F. M., & Van Kuijk, S. M. J. (2020). Does three-dimensional anatomy improve student understanding? A systematic review of the literature. *Clinical Anatomy*, 33(1), 25–33. <https://doi.org/10.1002/ca.23405>
94. Turney, B. W. (2007). Anatomy in a modern medical curriculum. *Annals of the Royal College of Surgeons of England*, 89(2), 104–107. <https://doi.org/10.1308/003588407X168244>
95. Vorstenbosch, M. A. T. M., Klaassen, T. P. F. M., Donders, A. R. T., Kooloos, J. G. M., Bolhuis, S. M., & Laan, R. F. J. M. (2013). Learning anatomy enhances spatial ability. *Anatomical Sciences Education*, 6(4), 257–262. <https://doi.org/10.1002/ase.1346>
96. Westberry, N., McNaughton, S., Billot, J., & Gaeta, H. (2015). Resituation or resistance? Higher education teachers' adaptations to technological change. *Technology, Pedagogy and Education*, 24(1), 101–116. <https://doi.org/10.1080/1475939X.2013.869509>
97. Wickramasinghe, N., Thompson, B. R., & Xiao, J. (2022). The opportunities and challenges of digital anatomy for medical sciences: Narrative review. *JMIR Medical Education*, 8(2), e34687. <https://doi.org/10.2196/34687>
98. Winne, P. H. (2020). Construct and consequential validity for learning analytics based on trace data. *Computers in Human Behavior*, 112, 106457. <https://doi.org/10.1016/j.chb.2020.106457>
99. Winne, P. H., & Hadwin, A. F. (1998). Studying as self-regulated learning. In D. J. Hacker, J. Dunlosky, & A. C. Graesser (Eds.), *Metacognition in educational theory and practice* (pp. 277–304). Lawrence Erlbaum Associates Publishers. <https://doi.org/10.4324/9781410602350-12>
100. Wirtu, A. T., & Manjatika, A. T. (2024). Challenges in sourcing bodies for anatomy education and research in Ethiopia: Pre and post COVID-19 scenarios. *Annals of Anatomy - Anatomischer Anzeiger*, 254, 152234. <https://doi.org/10.1016/j.aanat.2024.152234>
101. World Bank (2024, March 5). Global digitalization in 10 charts. <https://www.worldbank.org/en/news/immersive-story/2024/03/05/global-digitalization-in-10-charts>

102. Xiao, J., Donkin, R., & Lathe, S. (2025). Digital anatomy: A new frontier in health and medical science education. *Clinical Anatomy*. Advance online publication. <https://doi.org/10.1002/ca.70013>
103. Yammine, K., & Violato, C. (2015). A meta-analysis of the educational effectiveness of three-dimensional visualization technologies in teaching anatomy. *Anatomical Sciences Education*, 8(6), 525–538. <https://doi.org/10.1002/ase.1510>
104. Zimmerman, B. J. (2002). Becoming a self-regulated learner: An overview. *Theory Into Practice*, 41(2), 64–70. https://doi.org/10.1207/s15430421tip4102_2
105. Zingg, L., Häusler, M., Hein, J., Jecklin, S., Kottner, S., Gascho, D., Cavalcanti, N., Voinov, P., Götschi, T., Carrillo, F., Lagler, F., Fürnstahl, P., & Farshad, M. (2025). Using hologram-based augmented reality in anatomy learning: The TEACHANATOMY randomized trial. *Academic Medicine*, 100(6), 695–704. <https://doi.org/10.1097/ACM.0000000000006012>

ANNEXES

Annexe 1



OPEN ACCESS

EDITED BY
Apurba Patra,
All India Institute of Medical Sciences,
Bathinda, India

REVIEWED BY
Iuliana Raluca Gheorghe,
Carol Davila University of Medicine and
Pharmacy, Romania
Eve Mon Oo,
University of Medicine I, Myanmar

*CORRESPONDENCE
Valérie Defaweux
✉ valerie.defaweux@uliege.be

RECEIVED 07 October 2025
REVISED 07 December 2025
ACCEPTED 08 December 2025
PUBLISHED 05 January 2026

CITATION
Defaweux V, Prygiel O, Schieres L, Mutombo
Mwembo D, Etienne A-M, Fries A, Botte A,
Marchese C, Wouters M, Bonnet P,
Radermecker M and Lagler A (2026) Beyond
the gift: donor motivations and family
experiences as drivers of body donation
programs.
Front. Public Health 13:1720025.
doi: 10.3389/fpubh.2025.1720025

COPYRIGHT
© 2026 Defaweux, Prygiel, Schieres,
Mutombo Mwembo, Etienne, Fries, Botte,
Marchese, Wouters, Bonnet, Radermecker
and Lagler. This is an open-access article
distributed under the terms of the Creative
Commons Attribution License (CC BY). The
use, distribution or reproduction in other
forums is permitted, provided the original
author(s) and the copyright owner(s) are
credited and that the original publication in
this journal is cited, in accordance with
accepted academic practice. No use,
distribution or reproduction is permitted
which does not comply with these terms.

Beyond the gift: donor motivations and family experiences as drivers of body donation programs

Valérie Defaweux^{1*}, Olivier Prygiel¹, Louis Schieres¹,
David Mutombo Mwembo¹, Anne-Marie Etienne², Allyson Fries³,
Alain Botte¹, Caterina Marchese¹, Murielle Wouters¹,
Pierre Bonnet¹, Marc Radermecker¹ and Aude Lagler¹

¹Human Anatomy Laboratory, Department of Biomedical and Preclinical Sciences, Faculty of Medicine, University of Liège, Liège, Belgium, ²Department of Psychology, Health Psychology, Faculty of Psychology, Speech Therapy and Educational Sciences, University of Liège, Liège, Belgium, ³Laboratory of Human Histology, Department of Biomedical and Preclinical Sciences, Faculty of Medicine, University of Liège, Liège, Belgium

Background: Body donation to science provides indispensable resources for medical education and research, yet shortages remain widespread. Understanding the interplay between donor motivations and family experiences is essential to sustain donation programs and to position them as public health education initiatives.

Methods: We conducted a *mixed-methods exploratory study* at the University of Liège (Belgium), combining self-administered questionnaires from registered donors ($n = 104$) with surveys of donor families ($n = 10$). Quantitative data were analyzed descriptively and with nonparametric tests, while qualitative responses underwent thematic content analysis. The Behavior Change Wheel (BCW), the Protection Motivation Theory (PMT), and prosociality frameworks guided interpretation.

Results: Scientific utility was the leading motivation (56.7%), followed by symbolic meaning, altruism, and gratitude. Nearly all donors informed their relatives (96.2%), whose reactions varied by occupational category. Families expressed overall satisfaction but frequently described a "double bereavement" at death and at restitution. Word-of-mouth was the predominant channel of information (52.9%), though many respondents called for broader outreach. Within the PMT framework, donation was driven by high perceived response efficacy, reinforced self-efficacy (accessible information, family dialogue), and limited but salient emotional costs. Prosocial and altruistic factors (empathy, responsibility, symbolic legacy) complemented protective motivations, framing donation as a costly yet meaningful prosocial act.

Discussion: Integrating PMT and prosociality provides a novel model to explain why donation simultaneously addresses a perceived systemic shortage (protective motive) and a desire to contribute to the common good (altruistic motive). Family support functions as a key moderator, amplifying motivation and reducing perceived costs. Within the BCW, interventions should enhance capability (clear communication, bereavement support), expand opportunity (media campaigns, standardized rituals, faculty presence), and sustain motivation (student/educator testimonials, family recognition).

Conclusion: Body donation programs extend beyond logistics: they act as population-level health education and promotion initiatives, normalizing dialogue on death, solidarity, and legacy. Embedding integrative behavioral models into program design can strengthen institutional trust, support families, and ensure the sustainability of body donation worldwide.

KEYWORDS

anatomical education, behavior change wheel, bereavement, body donation, donor motivations, family perspectives, public health promotion

1 Introduction

Body donation to science represents a personal and altruistic act in which an individual bequeaths their body to a university center to contribute to medical education and scientific research (1, 2, 41). This practice, which is vital for the training of healthcare professionals and biomedical advancements, occurs within a context of growing demand for human cadavers, driven by the increasing number of medical students and medical faculties worldwide (3, 4). However, the shortage of available bodies constitutes a major challenge, exacerbated by cultural, ethical, and legal factors (5–8).

The decision to donate one's body is based on various motivations, including generosity, the desire to contribute to the advancement of scientific knowledge, and, at times, pragmatism concerning the costs or procedures related to traditional funeral arrangements (9, 10). However, the motivations of donors and the expectations of their families, which are often underexplored, are key factors in optimizing donation programs and communication strategies (11, 12). The sociocultural context and perceptions surrounding this practice vary by country, thus influencing both the profile of donors and the success of body donation initiatives (2, 10, 12, 41).

In Belgium, body donation practices are shaped by linguistic and cultural diversity, with regional variations in communication and public awareness. At the University of Liège, located in the French-speaking part of the country, the body donation program has experienced specific challenges and evolutions in recent years. Over the last decade, inquiries, pledges, and actual donations have fluctuated markedly, with 2020 representing a turning point coinciding with the COVID-19 pandemic. Inquiries declined from 382 (2014) to 104 (2020), pledges from 290 (2014) to 72 (2020), and actual donations from 94 (2015/2019) to 22 (2020). A gradual recovery followed, although none of these indicators had returned to pre-2020 levels by 2024 (Inquiries: ~240; Promises of Body Donation: ~140; Bodies Received: ~80). These dynamics provide the institutional and societal backdrop of the present exploratory study (13).

Despite the importance of understanding donation within this context, the voices of donors and families remain underrepresented in the literature. Family members, in particular, may experience what has been described as a “double loss”: first through the death of their loved one, and second through the temporary absence of the body during its use in teaching (14). Integrating their experiences into program development is essential not only for institutional trust but also for ensuring that body donation programs meet wider public health goals of transparency, equity, and social legitimacy.

The present study therefore aims to explore donor motivations and family perspectives in a Belgian university program through an

exploratory service evaluation. By drawing on the experiences of individuals who have formally registered as body donors, as well as those of the relatives involved in this process, the study offers an initial understanding of the population engaging with the University of Liège Body Donation Program. By combining descriptive statistics with narrative insights, it seeks to highlight the human and ethical dimensions of body donation, and to generate lessons for both medical education and institutional practice.

To address these gaps, this study was guided by the following objectives:

- (1) to examine the motivations of registered body donors at the University of Liège;
- (2) to describe and analyze the experiences of donor families;
- (3) to interpret these findings through integrative behavioral frameworks (BCW, PMT, prosociality) to inform institutional and public health practice.

2 Materials and methods

2.1 Study design

We conducted a mixed-methods exploratory study combining quantitative descriptive analyses and qualitative thematic analyses of open-ended responses. According to established classifications of mixed-methods research (15), this approach corresponds to a convergent parallel design, in which quantitative and qualitative data are collected during the same phase, analyzed separately, and integrated during interpretation to provide a comprehensive understanding of the phenomenon. The study was carried out at the University of Liège (ULiège) Body Donation Centre as part of an exploratory service evaluation aimed at informing institutional practice and medical education.

2.2 Populations and recruitment

Two populations were targeted:

- *Donors.* From 170 individuals who had pledged body donation in 2018, all were invited to participate. Inclusion criteria were age ≥ 18 years, proficiency in written French, informed consent, and questionnaire return before 31 March 2021. A total of 104 questionnaires were returned (response rate: 61.2%).
- *Families.* Relatives of deceased donors were contacted through funeral services between December 2020 and March 2021. Of 45

questionnaires distributed, 10 were completed and returned (22.2%).

As the ULiège program operates in French-speaking Wallonia, questionnaires were administered in French only.

Inferential statistics were applied exclusively to donor data; the small family sample was analyzed descriptively.

Content validity was reviewed by a panel of 17 experts (four donation specialists, ten healthcare professionals, and three potential donors, including one with prior family experience). Face validity was assessed during a pilot test with three potential donors. Readability was optimized (large font, clear layout) given the advanced age of many donors. Because the questionnaires consisted mainly of categorical and open-ended items, internal consistency measures such as Cronbach's alpha were not applicable. Instrument validity was ensured through expert review, piloting, and conceptual mapping to the BCW framework.

2.3 Instruments and validation

Two questionnaires were specifically developed:

- the *donor questionnaire* (17 items, 4 sections), which explored sociodemographic data, access to information, motivations, expectations, and advice for public awareness (Table 1);
- the *family questionnaire* (14 items, 3 sections), which addressed awareness of the donor's decision, experiences of bereavement, and satisfaction with the donation program (Table 2).

Both instruments were designed with reference to the *Behavior Change Wheel* (BCW) and its COM-B model (capability, opportunity, motivation) (16). Items were mapped conceptually to these dimensions (Annex A).

2.4 Data collection and management

Donor questionnaires were mailed with one postal reminder; family questionnaires were distributed via funeral services. Participation was voluntary and without compensation. Responses were anonymized, coded according to a predefined codebook, and securely stored. Identifiers and paper forms were destroyed after data entry.

2.5 Ethical considerations

The study “*Evaluation of the motivations and expectations of body donors and their families in the context of body donation to science at*

TABLE 1 Questionnaire for body donors—structure and items.

Section	Item	Question/variable	Response options
A. Sociodemographic data	1	Age	___ years
	2	Place of birth (City/Country)	(Free text)
	3	Gender	☐ Female ☐ Male ☐ Other
	4	Place of residence	(Free text)
	5	Occupation (before retirement)	(Free text)
	6	Education level	☐ Primary ☐ Secondary ☐ Higher nonuniversity ☐ Higher university ☐ Other: _____
	7	Nationality	(Free text)
B. Access to information channels	8	How did you learn about body donation to science?	☐ Radio ☐ Poster campaign ☐ Television ☐ University of Liège website ☐ Print media ☐ Word of mouth (Family/Friends/Colleagues) ☐ Other: _____
	9	Did you easily find the information about body donation to science?	☐ Yes ☐ No – Please specify: _____
C. Motivations	11	What motivated you to donate your body to science?	(Free text)
	12	Have you discussed your decision to donate your body to science with your relatives/family?	☐ Yes ☐ No
	13	What were their reactions?	(Free text)
	14	Why did you choose the University of Liège?	(Free text)
	15	Do you have specific expectations from our service regarding your family or relatives?	(Free text)
	16	Has your family influenced your decision to donate your body to science?	☐ Yes – Please specify: _____ ☐ No – Please specify: _____
D. Practical advice	17	In your opinion, how should the population be made more aware of body donation to science?	(Free text)

TABLE 2 Questionnaire for families of deceased body donors—structure and items.

Section	Item	Question/variable	Response options
A. Awareness of the donor's decision	1	Were you aware of your relative's decision to donate their body to science?	☐ Yes ☐ No
	2	Did you know their motivations?	(Free text)
	3	Do you think the donor's motivations were respected?	(Free text)
B. Family cohesion	4	How did you experience this bereavement?	(Free text)
	5	Do you think the grieving process is different when body donation to science is involved?	(Free text)
	6	Is there a way to make this grieving process easier?	(Free text)
	7	How much time elapsed between the death and the restitution of the donor's body?	(Free text)
	8	Was this waiting period reasonable?	☐ Yes ☐ No – Please specify: _____
C. Satisfaction with the University of Liège Body Donation Centre	9	Were you informed about the time of the body's restitution?	☐ Yes ☐ No – If no, would you have wanted to be informed? ☐ Yes ☐ No
	10	What type of funeral was carried out?	☐ Cremation ☐ Burial ☐ Unknown ☐ Other: _____
	11	Were you satisfied with the body donation service?	☐ Yes ☐ No – Please specify: _____
	12	What advice would you give to improve our services?	(Free text)
	13	What is your relationship to the deceased?	(Free text)
	14	Did you complete this questionnaire alone?	☐ Yes ☐ No – With whom? _____

the University of Liège” was reviewed by the Hospital-Faculty Ethics Committee of the University of Liège (ref. 2020/393). The committee confirmed that it did not fall under the Belgian law of 7 May 2004 on experiments involving human subjects. All participants provided written informed consent. Data handling complied with the General Data Protection Regulation (EU 2016/679).

2.6 Quantitative analysis

Categorical variables are presented as absolute numbers and percentages; continuous variables as medians with interquartile ranges (IQR). Normality of distributions was assessed by visual inspection and the Shapiro–Wilk test. Group comparisons used the Kruskal–Wallis test for continuous variables, while chi-square tests were applied for categorical variables with sufficient expected frequencies; Fisher's exact test was used when expected cell counts were small. Statistical significance was set at $p < 0.05$. Inferential analyses were limited to donor data; family responses were described qualitatively and quantitatively without inferential testing.

2.7 Qualitative analysis

Open-text responses were analyzed using *thematic content analysis*. A deductive coding frame based on the COM-B model was refined inductively to capture emergent themes. Two coders independently analyzed a subset of responses; discrepancies were resolved by consensus. *Illustrative quotations are reported to foreground participants' voices and provide context for numerical findings.*

3 Results

In line with the study objectives, the results are presented in two parts: (1) donor motivations, characteristics, and decision-making processes; and (2) experiences and perspectives of bereaved donor families. Quantitative and qualitative data are reported together when appropriate to enhance interpretation.

3.1 Quantitative analysis of donor responses

3.1.1 Study population

Of the 170 individuals registered as donors in 2018, 104 returned complete questionnaires (response rate: 61.2%). Exclusions were due to non-response ($n = 62$), explicit refusal ($n = 2$), death prior to receipt ($n = 1$), or incomplete data ($n = 1$).

3.1.2 Sociodemographic characteristics

The donor sample comprised 66 women (63.5%) and 38 men (36.5%), with a mean age of 72 years. Most participants were aged 60–79 years ($n = 72$, 69.2%). Almost all were Belgian nationals ($n = 100$, 96.2%), and the majority lived in Liège Province, where the university is located ($n = 82$, 78.9%). Regarding education, 43 donors (41.3%) had completed secondary studies and 36 (34.6%) non-university higher education. Most were employees or civil servants ($n = 58$, 55.8%). Links with medical/paramedical professions were reported by 12 donors (11.5%) and with education by 20 donors (19.2%) (Table 3).

TABLE 3 Sociodemographic characteristics of donors at the ULiège Body Donation Centre ($n = 104$).

Sociodémographic variables		
		n (%)
Sex	Male	38 (36.54)
	Female	66 (63.46)
Age	20–39 years	1 (0.96)
	40–59 years	12 (11.54)
	60–79 years	72 (69.23)
	≥ 80 years	19 (18.27)
Nationality	Belgian	100 (96.15)
	Other	4 (3.85)
Place of birth	Liège Province	62 (59.62)
	Belgium (other provinces)	29 (27.88)
	Abroad	13 (12.50)
Place of residence	Liège Province	82 (78.85)
	Belgium (other provinces)	22 (21.15)
	Abroad	0 (0)
Educational level	Primary	10 (9.62)
	Secondary	43 (41.35)
	Higher nonuniversity	36 (34.62)
	University	14 (13.46)
	NA	1 (0.96)
Occupation	Self-employed	17 (16.35)
	Employee/Civil servant	58 (55.77)
	Worker/Technician	21 (20.19)
	Unemployed	8 (7.69)
Profession related to medical/educational fields	Medical/Paramedical	12 (11.54)
	Teacher	20 (19.23)
	Nonmedical	72 (69.23)

3.1.3 Access to information about body donation

Word-of-mouth was the most frequent source of information ($n = 55$, 52.9%). Other sources included traditional or digital media ($n = 15$, 14.4%) and healthcare or teaching staff ($n = 10$, 9.6%). Twenty-four donors (23.1%) reported multiple sources. Almost all respondents ($n = 100$, 96.2%) found information easy to access.

When seeking additional information, donors most often turned to relatives ($n = 26$, 25.0%), the ULiège Body Donation Centre ($n = 20$, 19.2%), or physicians ($n = 11$, 10.6%). Preferred awareness strategies included traditional media and testimonials ($n = 50$, 48.1%), institutional or community relays ($n = 17$, 16.4%), and social media ($n = 7$, 6.7%) (Table 4).

3.1.4 Communication of the decision to relatives and family reactions

Almost all donors ($n = 100$, 96.2%) had discussed their decision with relatives. Reported family reactions were mainly favorable

($n = 66$, 63.5%), followed by astonishment ($n = 22$, 21.2%) or sadness/mixed feelings ($n = 16$, 15.4%).

Explanations included respect for the donor's choice ($n = 26$, 25.0%), affirmation of personal autonomy ($n = 9$, 8.7%), family agreement conditional on reflection or children's approval ($n = 4$, 3.9%), and previous family practice of donation ($n = 2$, 1.9%). Concerns about grieving were reported in 15 donors' families (14.4%) (Table 5).

3.1.5 Motivations, expectations, family influence, and choice of institution

The most frequent motivation was the desire to contribute to science ($n = 59$, 56.7%). Other motivations included symbolic meaning ($n = 17$, 16.4%), altruism ($n = 13$, 12.5%), gratitude for medical care ($n = 11$, 10.6%), and family-related reasons ($n = 3$, 2.9%). One donor (1.0%) did not specify a motivation.

Sixty-six donors (63.5%) expressed no specific expectations toward the institution. Among those who did, 25 (24.0%) asked for compassion toward families, six (5.8%) emphasized respect for their wishes, and two (1.9%) mentioned financial compensation.

Most donors ($n = 92$, 88.5%) declared their decision was not influenced by their family, while 12 (11.5%) reported some influence. Among the latter, explanations included respect for autonomy ($n = 13$, 12.5%) and family tradition of donation ($n = 5$, 4.8%).

The reasons for choosing the University of Liège were related primarily to geographical proximity (50%), followed by the institution's reputation or alumni connection (19.23%), recognition of the University Hospital (20.19%), and, more rarely, attachment to the city of birth (4.81%) (Table 6).

3.1.6 Determinants of body donation

Primary motivations for donation did not differ significantly (all $p > 0.05$) according to age, sex, occupation, medical background, or education.

However, several associations emerged:

- *Choice of institution.* Reasons for choosing ULiège were significantly associated with profession ($p = 0.012$), education level ($p = 0.012$), and primary donation motivation ($p = 0.004$). Health professionals and university graduates more often cited the reputation of the university or its hospital, whereas participants with primary/secondary education more frequently mentioned geographical proximity. Donors motivated by gratitude toward medical care were also more likely to highlight institutional recognition compared with those motivated by altruism or symbolic meaning.
- *Family reactions.* Reported family reactions were associated with occupational category ($p = 0.020$). Employees and civil servants more frequently reported supportive reactions, whereas workers and technicians more often described sadness, ambivalence, or absence of clear reaction.

No significant associations were found between sociodemographic characteristics and (i) information channels used, (ii) ease of access to information, (iii) having discussed the decision with relatives, or (iv) the degree of family influence on the decision (all $p > 0.05$).

TABLE 4 Information channels used by donors.

Information	<i>n</i> (%)
How did you first hear about body donation to science?	
Radio/TV, print media, awareness campaign, or website	15 (14.4)
From healthcare or teaching staff	10 (9.6)
Word of mouth	55 (52.9)
Multiple sources	24 (23.1)
Did you find information about body donation easily?	
Yes	100 (96.15)
No	4 (3.85)
Additional sources of information	
Internet search	5 (4.81)
Contact with the ULiège Body Donation Centre	20 (19.23)
Leaflet from the ULiège Body Donation Centre	2 (1.92)
Physicians	11 (10.58)
Funeral directors	2 (1.92)
Municipal administrations	3 (2.88)
Based on a relative's choice or family tradition	5 (4.81)
Advice from relatives	26 (25)
Multiple sources	3 (2.88)
No response	27 (25.96)
According to you, how should the population be made aware of body donation to science?	
Traditional media (Radio/TV/Print/Internet/Advertising/Testimonials)	50 (48.08)
Social media (Facebook/YouTube/Instagram)	7 (6.73)
Poster campaigns/leaflets	3 (2.88)
Word of mouth (Hospitals/Physicians/Mutual insurance/Cultural venues/Schools/Municipalities/Relatives)	17 (16.35)
Financial compensation	3 (2.88)
Solidarity message ("love and support for those left behind")	4 (3.85)
No response	20 (19.23)

3.2 Analysis of bereaved donor families' responses

This subanalysis focused on bereaved families of body donors whose remains were used for anatomical teaching at the University of Liège and subsequently returned to relatives via funeral services. Among 45 families contacted, 10 returned complete questionnaires (response rate: 22.2%). Respondents were mainly children ($n = 6$) and spouses ($n = 3$), with one joint spouse-child

TABLE 5 Donor communication with family regarding body donation decisions ($n = 104$).

Communication with family	<i>n</i> (%)
Have you discussed your decision to donate your body to science with your relatives/family?	
Yes	100 (96.15)
No	4 (3.85)
What were their reactions?	
Supportive	66 (63.46)
Surprised/Astonished	22 (21.15)
No reaction	0 (0)
Sadness or mixed feelings	16 (15.38)
Reasons for family reaction	
Donor's decision ("my body/my choice")	9 (8.65)
Family agreement after reflection/ approval of children desired	4 (3.85)
Family respects my choice	26 (25)
Family habit (they will also donate)	2 (1.92)
Family concern about managing grief, waiting time, inability to gather, or fear of the unknown	15 (14.42)
Surprise	11 (10.58)
Absence of close relatives/family	2 (1.92)
No response	35 (33.65)

response. In most cases (90%), questionnaires were completed individually.

3.2.1 Awareness of the donation decision

All families ($n = 10$, 100%) reported being informed of the donor's decision. In every case, the primary motivation was identified as contributing to science, particularly research and the training of healthcare professionals. Narratives frequently linked this motivation to prior personal or professional experiences with illness or healthcare. Eight families (80%) felt the donor's wishes had been fully respected, whereas two (20%) expressed uncertainty due to lack of detailed knowledge about how remains were used.

3.2.2 Bereavement experience

Most families ($n = 7$, 70%) described bereavement as particularly challenging, often characterized as a "double loss"—first at the time of death and again at the return of the remains. Two families (20%) reported coping without difficulty, citing long-term preparation, and one (10%) found comfort in honoring the donor's wishes.

Families suggested several improvements to ease bereavement: reducing the delay between death and restitution ($n = 2$, 20%), providing better informational and emotional support ($n = 2$, 20%), notifying families 1 month in advance of the return ($n = 1$, 10%),

offering reassurance about respectful handling of the body ($n = 1$, 10%), ensuring faculty presence at restitution ($n = 1$, 10%), and formal expressions of gratitude ($n = 1$, 10%). Two families (20%) indicated that no further support was needed.

3.2.3 Interval between death and return of remains

At ULiège, restitution delays range from 3 months to 3 years. In this cohort, six families (60%) reported a delay of ≤ 6 months, three (30%) between 7–12 months, and one (10%) > 12 months. Seven families (70%) considered this delay reasonable. All families were informed of the return date. Cremation was the most common funeral practice ($n = 6$, 60%), followed by burial ($n = 3$, 30%).

3.2.4 Satisfaction with the body donation program

Satisfaction was unanimous ($n = 10$, 100%). Families valued honoring the donor's wishes ($n = 4$, 40%), contributing to science ($n = 4$, 40%), and setting an example for others ($n = 2$, 20%). No dissatisfaction was reported. Suggested improvements included advance notification of restitution ($n = 3$, 30%), direct faculty contact with families ($n = 2$, 20%), and broader public awareness of the value of body donation ($n = 1$, 10%). Three families (30%) reported that no changes were needed, while one (10%) suggested consolidating the grieving process into a single phase to avoid the emotional strain of "double bereavement."

3.2.5 Thematic synthesis

Qualitative analysis of open-text responses identified three domains (Table 7):

Communication and understanding. Families consistently described donation as motivated by service to science, often grounded in health-related experiences.

Impact on grieving. Many highlighted emotional strain linked to a perceived two-stage bereavement, while others described resilience facilitated by preparation or alignment with donor values.

Satisfaction and program enhancement. Despite unanimous satisfaction, families suggested refinements to strengthen communication, provide earlier notification, reassure ethical respect for remains, and acknowledge donation through formal recognition.

4 Discussion

Optimizing body donation programs requires more than operational efficiency; it demands a systemic understanding of the psychological, social, and cultural determinants shaping donor decisions and family experiences. As emphasized by Bagian et al. (17), institutional performance depends as much on relational and communicational dynamics as on administrative procedures. Our findings, interpreted through the Behavior Change Wheel (BCW), highlight key levers to strengthen trust, enhance engagement, and ensure the sustainability of donation programs. Four main themes emerge: (i) the hierarchy of motivations for donation, (ii) the autonomy of decision-making, (iii) the role of information channels, and (iv) the family experience of donation.

TABLE 6 Donors' motivations for body donation to science at the University of Liège ($n = 104$).

Motivation	$n(\%)$
What motivated you to donate your body to science?	
Altruism	13 (12.5)
Desire to contribute to science (research/training of future physicians and surgeons)	59 (56.73)
Giving meaning to death	17 (16.35)
Gratitude for medical care received	11 (10.58)
Family reasons (absence of relatives/family tradition)	3 (2.88)
No response	1 (0.96)
Do you have specific expectations from our service regarding your relatives/family?	
No expectations	66 (63.46)
Respect for the body	1 (0.96)
Compassion and support for families	25 (24.04)
Respect for the donor's wishes	6 (5.77)
Financial compensation	2 (1.92)
No response	4 (3.85)
Has your family influenced your decision to donate your body to science?	
Yes	12 (11.54)
No	92 (88.46)
Reasons for family influence on donation decision	
Personal decision ("my body/my choice")	50 (48.08)
Family agreement after reflection/approval of children desired	3 (2.88)
Family respects my choice	13 (12.50)
Family tradition (they will also donate)	5 (4.81)
Family concern about grief, waiting period, inability to gather, or fear of the unknown	2 (1.92)
Surprise	1 (0.96)
Absence of close relatives/family	6 (5.77)
No response	24 (23.08)
Why did you choose the University of Liège?	
Proximity	52 (50)
Reputation of ULiège, link with alma mater	20 (19.23)
Recognition of the University Hospital	21 (20.19)
Attachment to city of birth	5 (4.81)
Only institution known	6 (5.77)

4.1 Scientific utility as the dominant motivation

Consistent with international literature, our study confirms that the leading motivation for body donation is the desire to contribute to science and education (56.7%), followed by symbolic meaning,

TABLE 7 Summary of survey responses from bereaved donor families, combining quantitative data and expanded representative quotations.

Domain	Quantitative findings	Expanded representative qualitative quotes
Awareness of the donation decision	100% informed; 100% identified main motivation as contributing to science; 80% felt wishes were respected; 20% unsure	"Since always, it was his wish to donate his body to science."/"To advance medicine."/"To advance science — as a nurse, she was oriented toward helping others; she had two disabled grandchildren and hoped science could help them and others."/"He suffered from severe scoliosis and hoped to contribute to understanding and curing this condition."/"We hope the donation was useful; we trust it was."
Bereavement experience	70% reported "double loss"; 20% no difficulty; 10% comforted by donor's will	"It felt like losing him twice, even if we knew it was coming."/"A double bereavement — the return was a shock, and everything had to start over psychologically."/"We were prepared for over 10 years and there was no hesitation at the time of death."/"Without difficulty, as she had often spoken of this wish, although medical staff at the ICU seemed unfamiliar with the process."
Suggestions to ease bereavement	Reduce delay (20%); better info/support (20%); notify 1 month prior (10%); reassure ethical respect (10%); faculty contact at return (10%); formal recognition (10%); no help needed (20%)	"Reduce the time between removal and return of the body — is it materially possible for the University?"/"Provide more information for the children; for the spouse, everything was clear."/"Reassure us about the respect given to the body throughout the process."/"Support the mental strength of the surviving spouse."/"Contact families personally to explain how things happen — it would feel less anonymous."/"Acknowledge families with an official thank-you."
Interval between death and return	≤ 6 months: 60%; 7–12 months: 30%; > 12 months: 10%; 70% considered reasonable	–
Funeral type	Cremation: 60%; Burial: 30%	–
Satisfaction with the program	100% satisfied; reasons: honoring donor's will (40%), contributing to science (40%), exemplary gesture (20%)	"It was her choice, and I respected it."/"It was my mother's will, and I honored it."/"For science to progress in fighting cancer."/"I hope this donation will help students understand the human body better."/"Absolutely — I have personally chosen to do the same."
Suggestions for improvement	Advance notification (30%); faculty contact at return (20%); public awareness (10%); no change (30%); single-phase grief (10%)	"Notify us a month before the funeral date."/"Increase public and hospital awareness of the importance of body donation for medical training."/"Have a faculty representative present before the departure of the deceased."/"Avoid making families grieve twice — in France, the body does not return, so grieving starts immediately."

altruism, and gratitude. Previous work has highlighted this primacy of scientific utility (9, 10, 12) while also emphasizing the multifactorial nature of motivations, where altruism, gratitude, and family traditions may coexist. Interestingly, pragmatic considerations such as reducing funeral costs—frequent in other contexts (12)—were nearly absent in our sample.

This suggests that body donation is not reducible to a single driver but emerges from a multidimensional reflection that combines scientific contribution with personal and existential values. While organ donation is often framed around altruism and duty (18, 19), whole-body donation appears to be a more reflexive act, tied to educational and symbolic significance. Our findings therefore enrich the literature by clarifying the relative hierarchy of these drivers in a Belgian cohort.

4.2 Decision-making autonomy embedded in social contexts

Nearly nine out of ten donors reported making their decision independently, with limited direct family influence. However, most had discussed their choice with relatives, whose reactions varied by occupational category: employees/civil servants more often expressed support, whereas workers/technicians more frequently reported sadness or ambivalence. These findings highlight what Sanner (20, 21) termed conditional autonomy: while the decision is framed as "my body, my choice," its reception and legitimacy remain socially situated.

International studies converge on this interpretation: motivations are primarily personal (9, 10), yet family dialog plays a key role in legitimizing the choice and facilitating grief (7, 12). Cultural and religious frameworks also condition this autonomy, as seen in studies across Europe, South Africa, and Asia (5, 22, 23). Our data thus support the idea that body donation is both a profoundly individual decision and a relational act negotiated within family and cultural networks.

4.3 Word-of-mouth as the main communication channel

More than half of our donors first heard of body donation through word-of-mouth, underlining the central role of interpersonal trust in initial engagement. Yet nearly half also called for broader media campaigns to ensure wider public visibility. This duality reflects the complementarity of communication channels observed elsewhere: interpersonal networks provide credibility, whereas mass media and social platforms expand reach (24–26).

Anatomy educators and students also emerge as powerful intermediaries. Nearly one-third of our donors had professional ties to healthcare or education, which positions them as credible ambassadors of donation. Prior studies confirm that students and educators serve as primary messengers for donation values (27, 28). However, exposure to dissection can generate ambivalence (29, 30), underscoring the need for pedagogical framing and symbolic rituals. Gratitude ceremonies, as described by Guo et al. (31), play a critical

offering reassurance about respectful handling of the body ($n = 1$, 10%), ensuring faculty presence at restitution ($n = 1$, 10%), and formal expressions of gratitude ($n = 1$, 10%). Two families (20%) indicated that no further support was needed.

3.2.3 Interval between death and return of remains

At ULiège, restitution delays range from 3 months to 3 years. In this cohort, six families (60%) reported a delay of ≤ 6 months, three (30%) between 7–12 months, and one (10%) > 12 months. Seven families (70%) considered this delay reasonable. All families were informed of the return date. Cremation was the most common funeral practice ($n = 6$, 60%), followed by burial ($n = 3$, 30%).

3.2.4 Satisfaction with the body donation program

Satisfaction was unanimous ($n = 10$, 100%). Families valued honoring the donor's wishes ($n = 4$, 40%), contributing to science ($n = 4$, 40%), and setting an example for others ($n = 2$, 20%). No dissatisfaction was reported. Suggested improvements included advance notification of restitution ($n = 3$, 30%), direct faculty contact with families ($n = 2$, 20%), and broader public awareness of the value of body donation ($n = 1$, 10%). Three families (30%) reported that no changes were needed, while one (10%) suggested consolidating the grieving process into a single phase to avoid the emotional strain of “double bereavement.”

3.2.5 Thematic synthesis

Qualitative analysis of open-text responses identified three domains (Table 7):

Communication and understanding. Families consistently described donation as motivated by service to science, often grounded in health-related experiences.

Impact on grieving. Many highlighted emotional strain linked to a perceived two-stage bereavement, while others described resilience facilitated by preparation or alignment with donor values.

Satisfaction and program enhancement. Despite unanimous satisfaction, families suggested refinements to strengthen communication, provide earlier notification, reassure ethical respect for remains, and acknowledge donation through formal recognition.

4 Discussion

Optimizing body donation programs requires more than operational efficiency; it demands a systemic understanding of the psychological, social, and cultural determinants shaping donor decisions and family experiences. As emphasized by Bagian et al. (17), institutional performance depends as much on relational and communicational dynamics as on administrative procedures. Our findings, interpreted through the Behavior Change Wheel (BCW), highlight key levers to strengthen trust, enhance engagement, and ensure the sustainability of donation programs. Four main themes emerge: (i) the hierarchy of motivations for donation, (ii) the autonomy of decision-making, (iii) the role of information channels, and (iv) the family experience of donation.

TABLE 6 Donors' motivations for body donation to science at the University of Liège ($n = 104$).

Motivation	$n(\%)$
What motivated you to donate your body to science?	
Altruism	13 (12.5)
Desire to contribute to science (research/training of future physicians and surgeons)	59 (56.73)
Giving meaning to death	17 (16.35)
Gratitude for medical care received	11 (10.58)
Family reasons (absence of relatives/family tradition)	3 (2.88)
No response	1 (0.96)
Do you have specific expectations from our service regarding your relatives/family?	
No expectations	66 (63.46)
Respect for the body	1 (0.96)
Compassion and support for families	25 (24.04)
Respect for the donor's wishes	6 (5.77)
Financial compensation	2 (1.92)
No response	4 (3.85)
Has your family influenced your decision to donate your body to science?	
Yes	12 (11.54)
No	92 (88.46)
Reasons for family influence on donation decision	
Personal decision (“my body/my choice”)	50 (48.08)
Family agreement after reflection/approval of children desired	3 (2.88)
Family respects my choice	13 (12.50)
Family tradition (they will also donate)	5 (4.81)
Family concern about grief, waiting period, inability to gather, or fear of the unknown	2 (1.92)
Surprise	1 (0.96)
Absence of close relatives/family	6 (5.77)
No response	24 (23.08)
Why did you choose the University of Liège?	
Proximity	52 (50)
Reputation of ULiège, link with alma mater	20 (19.23)
Recognition of the University Hospital	21 (20.19)
Attachment to city of birth	5 (4.81)
Only institution known	6 (5.77)

4.1 Scientific utility as the dominant motivation

Consistent with international literature, our study confirms that the leading motivation for body donation is the desire to contribute to science and education (56.7%), followed by symbolic meaning,

role in embedding respect and humanism within anatomy education and extending these values to society.

4.4 Family experiences: satisfaction and the challenge of “double bereavement”

All families in our study reported satisfaction with the program and emphasized respect for donor wishes and scientific contribution. Yet many described the grieving process as fragmented, marked by a perceived “double bereavement”—at the time of death and later at the restitution of remains. This echoes thanatology research showing that disrupted rituals and delayed closure can complicate mourning (14, 32).

At the same time, some families reported that donation provided comfort, transforming loss into a meaningful contribution to society. This ambivalence, also observed in prior studies (33, 34), highlights the importance of tailored family support. Suggestions emerging from our cohort—timely notifications, reassurance about respectful handling, and faculty presence at restitution—mirror recommendations in the international literature for strengthening transparency, recognition, and ritual support (10, 31).

4.5 Toward an integrative model: protection motivation theory and prosociality

Beyond the BCW/COM-B framework, our findings can be interpreted through an integrative model combining Protection Motivation Theory (PMT) and prosocial and altruistic processes. PMT posits that behavior results from both a threat appraisal and a coping appraisal (35–37). In the context of body donation, the threat dimension takes two forms: a systemic threat (the shortage of bodies compromising the quality of medical training, as reported by a majority of donors) and an existential threat (awareness of mortality and the search for meaning at the end of life).

On the coping appraisal side, our data indicate that:

- Perceived response efficacy is central, with more than half of respondents ranking scientific and educational contribution as the primary motivation (56.7%).
- Self-efficacy is strengthened by the accessibility of information and by the fact that nearly all donors informed their families (96.2%), reflecting a sense of control over the decision.
- Perceived costs are mainly emotional and ritual in nature, expressed by families through the experience of a “double bereavement” (at the time of death and at the restitution of the body), and modulated by family reactions that varied according to socio-professional background.

Taken together, these elements delineate a protective motivation, whereby body donation is construed as both a response to a collective threat (insufficient resources for medical education) and a way of attributing meaning to one's own finitude.

In parallel, prosocial and altruistic drivers illuminate other dimensions of our results: empathy toward future generations,

social responsibility, gratitude toward caregivers, and the *warm-glow* of a valued contribution. This interpretation is consistent with the literature on costly prosocial behaviors (38, 39) and supports the view that body donation is embedded in a public good logic. Our data confirm this perspective: although explicit altruism was not the most frequently cited motivation, it underlies the observed motivational hierarchy and emerges in families' suggestions for program improvement (rituals, institutional recognition).

Thus, integrating PMT with prosociality provides a framework in which body donation simultaneously responds to a protective logic (mitigating a threatening shortage, making sense of mortality) and an altruistic logic (supporting student education, contributing to the common good). The almost systematic presence of family support can be understood as both a motivational amplifier and a perceived cost reducer, consistent with meta-analyses linking social support and prosocial behavior (40). This dual mechanism is illustrated in Figure 1, which conceptualizes body donation as the outcome of an interaction between protective and altruistic motivations.

4.6 Implications within the BCW framework

When transposed into the BCW/COM-B framework, this integrative model highlights several concrete levers for intervention:

- *Capability*: Clear and accessible information materials (brochures, videos, FAQs), combined with structured bereavement anticipation pathways (standardized timelines, designated faculty contact points), reduce uncertainty, enhance self-efficacy, and mitigate emotional costs.
- *Opportunity*: Expanding communication channels beyond word-of-mouth (community campaigns, hospital-based relays, trained educators), implementing standardized advance notices for body restitution, and ensuring faculty presence along with ceremonies of gratitude extend outreach, reinforce prosocial norms, and diminish ritual-related costs.
- *Motivation*: Testimonies from students and educators, concrete feedback on the pedagogical use of donations, structured scripts for family discussions, checklists, and visible forms of institutional recognition (letters, symbols, ceremonies) strengthen perceived response efficacy, sustain self-efficacy, and activate altruistic drivers such as the *warm-glow* effect or symbolic legacy.

These domains and their applications are summarized in Table 8, which integrates empirical findings with BCW-inspired interventions and specific targets linked to PMT and prosociality. Several of these initiatives are already being implemented at the University of Liège (awareness campaigns, community partnerships, ceremonies of gratitude). The analysis of trends from 2014 to 2024 suggests that such strategies have contributed to the post-pandemic recovery in pledges and actual body donations.

4.7 Limitations of the study

This mixed-methods exploratory study has several limitations that must be considered when interpreting the findings.

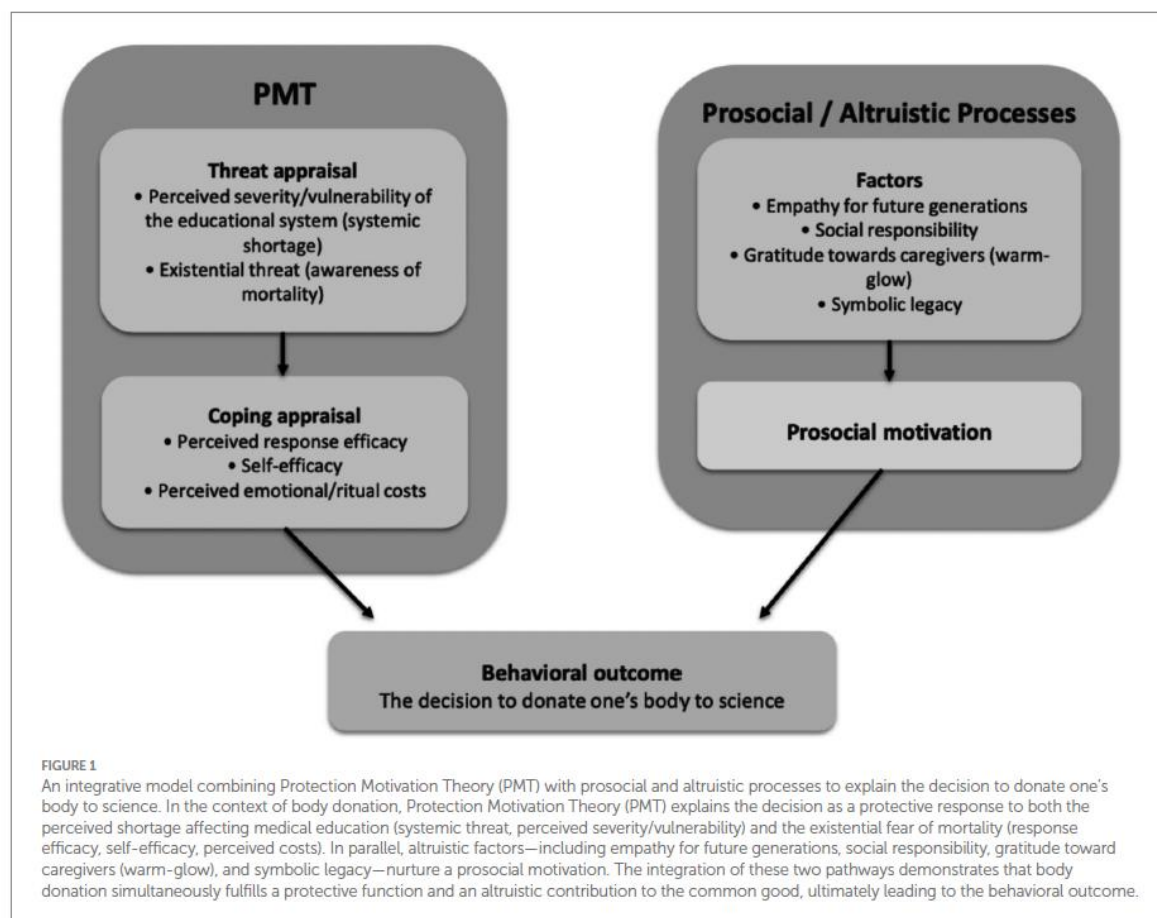


TABLE 8 Application of the COM-B framework to body donation: determinants, interventions, expected outcomes, and PMT/prosociality targets.

COM-B dimension (capability, opportunity, motivation)	Identified determinants	Examples of interventions	Expected outcomes	PMT/prosociality targets
Capability (knowledge and emotional resources)	Limited understanding of procedures; difficulty anticipating restitution; emotional vulnerability of families	Clear brochures/videos; transparent communication on pedagogical use; bereavement anticipation pathways (standardized timelines, designated contact points)	Improved comprehension; reduced uncertainty; better supported grieving process	↓ Perceived costs; ↑ Self-efficacy; stronger sense-making (social value)
Opportunity (social and environmental context)	Predominance of word-of-mouth; limited outreach; teachers as intermediaries	Media campaigns (TV/radio/press/web); community & hospital relays; teacher training; standardized restitution notice; faculty presence; ceremonies of gratitude	Broader audience; strengthened legitimacy; consolidated culture of respect; reduced ritual costs	↑ Perceived efficacy; ↑ Prosocial norms; ↓ Ritual/emotional costs ("double bereavement")
Motivation (reflective and automatic)	Scientific utility as primary driver; altruism, gratitude, search for meaning; ambivalent family reactions	Student/teacher testimonials; concrete pedagogical use cases; structured family discussion scripts; checklists; ethical reassurance/traceability; formal recognition of families	Reinforced pride and legitimacy; symbolic transformation of loss; increased long-term adherence	↑ Response efficacy; ↑ Self-efficacy; warm-glow / recognition

First, the response rate among families of deceased donors was low (22.2%), which restricts the generalizability of results regarding bereavement and satisfaction. Families who chose to respond may represent those with particularly strong views, introducing potential self-selection bias. Silent or ambivalent perspectives are therefore likely underrepresented, a challenge frequently noted in research on end-of-life experiences (32, 33).

Second, the small family sample ($n = 10$) limits statistical power and precludes multivariable analysis. Findings from this group should thus be viewed as exploratory, highlighting themes that align with international literature—such as “double bereavement” and the importance of symbolic recognition—rather than establishing definitive trends.

Third, the cross-sectional design captures donor and family perspectives at a single point in time. It cannot account for how motivations, experiences, or satisfaction may evolve over the course of bereavement. Longitudinal studies would be necessary to explore these dynamics more fully.

Fourth, the study population was geographically concentrated in Liège and predominantly Belgian. Cultural, religious, and legal contexts vary widely across countries, and caution is needed when extrapolating these findings to other settings. Multicentric comparisons could help distinguish local from universal determinants of donation.

Fifth, the qualitative component relied exclusively on written responses to self-administered questionnaires. While this approach allowed for efficient and anonymous data collection on sensitive issues such as grief, ambivalence, and motivations, it inherently limited the depth, contextualization, and emotional nuance of participants' accounts. Written responses tend to be more concise and less elaborated than data generated through interviews, which restricts the level of interpretive richness that can be achieved. Future studies incorporating interviews or focus groups would therefore provide a more detailed and dynamic understanding of donor motivations and family experiences.

Finally, while the self-administered questionnaires allowed for efficient data collection, they limited the depth of responses on sensitive issues such as grief or ambivalence. Complementary qualitative approaches, such as interviews or focus groups, could provide richer insights.

Despite these limitations, the study provides valuable empirical evidence in an underexplored field and offers practical directions for optimizing body donation programs.

4.8 Future research directions

This study opens several avenues for future research and program development. First, multicentric studies across different linguistic, cultural, and legal contexts could test the transferability of the integrative PMT–prosociality model and identify context-specific determinants of donation. Second, longitudinal designs following donors and families over time—from the pledge of donation to restitution and beyond—would clarify how motivations, expectations, and bereavement trajectories evolve and how institutional practices shape these trajectories. Third, in-depth qualitative work (e.g., semi-structured interviews or focus groups) with under-represented or non-responding families could capture silent forms of ambivalence,

resistance, or mistrust that are less accessible through questionnaires. Finally, intervention studies evaluating BCW-informed strategies (communication tools, bereavement pathways, gratitude ceremonies, feedback to families) could generate robust evidence to guide anatomy departments, body donation centers, ethics committees, and public health authorities in designing ethically robust, family-sensitive, and sustainable donation pathways.

4.9 Conclusion

This exploratory study makes three principal contributions. *Empirically*, it provides rare and systematic data on donor motivations and family experiences within a European cohort. *Conceptually*, it advances an integrative model combining Protection Motivation Theory (PMT) and prosociality, framing body donation simultaneously as a response to existential threat and as an expression of social responsibility. *Operationally*, it translates these findings into actionable levers within the BCW/COM-B framework, proposing targeted interventions to enhance perceived efficacy, reduce emotional costs, and strengthen practices of recognition.

From a *public health perspective*, body donation programs emerge not only as institutional services but also as initiatives of education and health promotion at the population level, where discussions on death, solidarity, and legacy are normalized. Interventions that encourage family dialogue, foster transparency, and acknowledge donor contributions may broaden engagement while shielding vulnerable families from the experience of fragmented grief.

Although limited by sample size and geographical scope, the convergence with international literature suggests that the issues identified resonate beyond Belgium. More firmly embedding body donation within educational and public health agendas offers a promising avenue to reinforce institutional trust, support families, and ensure the sustainable growth of donation programs worldwide.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Hospital-Faculty Ethics Committee of the University of Liège (ref. 2020/393). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

VD: Writing – original draft, Writing – review & editing. OP: Writing – review & editing. LS: Writing – review & editing. DM: Writing – review & editing. A-ME: Writing – review & editing. AF: Writing – review & editing. AB: Writing – review & editing. CM: Writing – review & editing. MW: Writing – review & editing. PB:

Writing – review & editing. MR: Writing – review & editing. AL: Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgments

The authors acknowledge Christiane Kalak Tchoupou for initiating this research and Cécile Rode for assistance with formatting and secretarial support.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Estai, M., and Bunt, S. Best teaching practices in anatomy education: a critical review. *Ann Anat.* (2016) 208:151–7. doi: 10.1016/j.aanat.2016.02.010
- Riederer, BM. Body donations today and tomorrow: what is best practice and why? *Clin Anat.* (2016) 29:11–8. doi: 10.1002/ca.22641
- Gangata, H., Ntuba, P., Akol, P., and Louw, G. The reliance on unclaimed cadavers for anatomical teaching by medical schools in Africa. *Anat Sci Educ.* (2010) 3:174–83. doi: 10.1002/ase.157
- Habicht, J.L., Kiessling, C., and Winkelmann, A. Bodies for anatomy education in medical schools: an overview of the sources of cadavers worldwide. *Acad Med.* (2018) 93:1293–300. doi: 10.1097/ACM.0000000000002227
- Abbasi Asl, J., Nikzad, H., Taherian, A., Atlasi, MA., Naderian, H., Mousavi, G., et al. Cultural acceptability and personal willingness of Iranian students toward cadaveric donation. *Anat Sci Educ.* (2017) 10:120–6. doi: 10.1002/ase.1634
- Brenner, E., Bley, R.L., de Caro, R., Catereniuc, I., Chirculescu, A.R., Destrieux, C., et al. The legal and ethical framework governing body donation in Europe – 2nd update on current practice. *Ann Anat.* (2024) 252:152195. doi: 10.1016/j.aanat.2023.152195
- Hutchinson, EE, Kramer, B., Brits, DM., and Billings, BK. The law, ethics and body donation: a tale of two bequeathal programs. *Anat Sci Educ.* (2020) 13:512–9. doi: 10.1002/ase.1922
- Jiang, J., Zhang, M., Meng, H., Wang, L., Li, W., Yang, F., et al. Demographic and motivational factors affecting the whole-body donation programme in Nanjing, China: a cross-sectional survey. *BMJ Open.* (2020) 10:e035539. doi: 10.1136/bmjopen-2019-035539
- Bolt, S., Venbrux, E., Eisinga, R., Kuks, JB., Veening, JG., and Gerrits, PO. Motivation for body donation to science: more than an altruistic act. *Ann Anat.* (2010) 192:70–4. doi: 10.1016/j.aanat.2010.02.002
- Cornwall, J., Perry, GF, Louw, G., and Stringer, MD. Who donates their body to science? An international, multicenter, prospective study. *Anat Sci Educ.* (2012) 5:208–16. doi: 10.1002/ase.1278
- Greene, SJ., Collins, AJ., and Rosen, L. A memorial ceremony for anatomical donors: an investigation of donor family and student responses. *Med Sci Educ.* (2018) 28:71–9. doi: 10.1007/s40670-017-0504-3
- Smith, CF, Munro, R., Davies, DC., Wilkinson, T., Shaw, H., Claridge, K., et al. Understanding beliefs, preferences and actions amongst potential body donors. *Anat Sci Educ.* (2023) 16:224–36. doi: 10.1002/ase.2204
- RTBF Info (2021). Don de corps à la science: les instituts d'anatomie observent une pénurie de donateurs. RTBF Available online at: <https://www.rtbf.be/article/don-de-corps-a-la-science-les-instituts-d-anatomie-observent-une-penurie-de-donneurs-10976675> (Accessed November 2025).
- Stroebe, M., Schut, H., and Boerner, K. Cautioning health-care professionals: bereaved persons are misgrieved through the stages of grief. *Omega (Westport).* (2017) 74:455–73. doi: 10.1177/0030222817691870

Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. Generative AI (ChatGPT) was used to assist in language editing and minor text restructuring. The authors verified all content, data, and interpretations, and take full responsibility for the accuracy and originality of the manuscript. No data, results, analyses, or conceptual content were generated by AI.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

- Creswell, JW, and Clark, VLP. Designing and conducting mixed methods research. Thousand Oaks, CA: Sage Publications (2017).
- Michie, S., van Stralen, MM., and West, R. The behaviour change wheel: a new method for characterising and designing behaviour change interventions. *Implement Sci.* (2011) 6:42. doi: 10.1186/1748-5908-6-42
- Bagian, LK., Davis, DC., Parker, RC., Mosley, CF., and Balta, JY. Giving a voice to our silent teachers: whole body donation from the donor perspective at one donation program in the United States. *Anat Sci Educ.* (2024) 17:893–908. doi: 10.1002/ase.2410
- Morgan, SE., Miller, J., and Arasaratnam, LA. Signing cards, saving lives: an evaluation of the worksite organ donation promotion project. *Commun Monogr.* (2002) 69:253–73. doi: 10.1080/03637750216540
- Rodrigue, JR., Cornell, DL., and Howard, RJ. Attitudes toward financial incentives, donor authorization, and presumed consent among next-of-kin who consented vs. refused organ donation. *Transplantation.* (2006) 81:1249–56. doi: 10.1097/01.tp.0000203165.49905.4a
- Sanner, MA. Exchanging spare parts or becoming a new person? People's attitudes toward receiving and donating organs. *Soc Sci Med.* (2001) 52:1491–9. doi: 10.1016/S0277-9536(00)00258-6
- Sanner, MA. People's attitudes and reactions to organ donation. *Mortality.* (2006) 11:133–50. doi: 10.1080/13576270600615351
- Matshipi, MN., and De Gama, BZ. Influence of religio-cultural beliefs on whole-body donation: a quantitative analysis of a predominantly south African Pedi community. *Ann Anat.* (2024) 256:152315. doi: 10.1016/j.aanat.2024.152315
- Šink, Ž., Tonin, G., Umek, N., and Cvetko, E. Attitudes of Slovenian students towards whole-body donation, organ donation, and the use of donated bodies in medical education. *BMC Med Educ.* (2024) 24:1535. doi: 10.1186/s12909-024-06569-7
- Febrero, B., Almela-Baeza, J., Ros-Madrid, I., Arias, JA., Ruiz-Manzanera, JJ., Jiménez-Masculán, MI., et al. The new age of organ donation—what factors have an influence on the attitude of older people? An attitudinal survey in southeastern Spain. *Int J Environ Res Public Health.* (2022) 19:8524. doi: 10.3390/ijerph19148524
- Gong, F., Jia, Y., Zhang, H., Cao, J., Jia, Y., Sun, X., et al. Media use and willingness to accept organ donation: a latent profile analysis among residents from 120 cities in China. *Front Public Health.* (2022) 10:1000158. doi: 10.3389/fpubh.2022.1000158
- Olsacher, A., Bade, C., Ehlers, J., Freitag, B., and Fehring, L. Messaging strategies for communicating health-related information in social media: a content and effectiveness analysis of organ donation posts on Instagram in Germany. *BMC Public Health.* (2023) 23:867. doi: 10.1186/s12889-023-15736-2
- Behera, S., Chowdhury, RK., Sar, M., and Mishra, SK. Awareness, knowledge, and attitude toward body donation among medical and paramedical students. *Natl J Clin Anat.* (2023) 12:20–6. doi: 10.4103/NJCA.NJCA_219_22
- Hildebrandt, S. The role of history and ethics of anatomy in medical education. *Anat Sci Educ.* (2019) 12:425–31. doi: 10.1002/ase.1852

29. Ganapathy, A, Joy, P, Rout, S, and Gaikwad, M. The attitude of medical students toward voluntary body donation: a single institute survey and narrative review of global trends. *Cureus*. (2023) 15:e40775. doi: 10.7759/cureus.40775
30. Lai, ER, Rukavina, NA, Wisco, JJ, and Zumwalt, AC. Comparing the emotional experiences of students in similar dissection- and prosection-based medical gross anatomy courses: a mixed-methods study. *Anat Sci Educ*. (2023) 16:926–42. doi: 10.1002/ase.2281
31. Guo, K, Luo, T, Zhou, LH, Xu, D, Zhong, G, Wang, H, et al. Cultivation of humanistic values in medical education through anatomy pedagogy and gratitude ceremony for body donors. *BMC Med Educ*. (2020) 20:440. doi: 10.1186/s12909-020-02292-1
32. Bernard, J, and Le Grand-Séville, C. Le don du corps, cet inconnu. *Études Mort*. (2016) 149:7–14. doi: 10.3917/eslm.149.0007
33. Mahat-Shamir, M, Hamama-Raz, Y, and Leichtentritt, RD. Body perception and organ donation: bereaved parents' perspectives. *Qual Health Res*. (2019) 29:1623–33. doi: 10.1177/1049732319827520
34. Science Care. (2025). Body donation: supporting families and advancing science. Available online at: <https://www.sciencecare.com> (Accessed November 2025).
35. Balla, J, and Hagger, MS. Protection motivation theory and health behaviour: a conceptual review. *Health Psychol Rev* [Epub ahead of print]. (2025) 19:145–71. doi: 10.1080/17437199.2024.2413011
36. Hedayati, S, Damghanian, H, Farhadinejad, M, and Rastgar, AA. Meta-analysis on application of protection motivation theory in preventive behaviors against COVID-19. *Int J Disaster Risk Reduct*. (2023) 94:103758. doi: 10.1016/j.ijdrr.2023.103758
37. Rogers, RW. A protection motivation theory of fear appeals and attitude change. *J Psychol*. (1975) 91:93–114. doi: 10.1080/00223980.1975.9915803
38. Neumann-Böhme, S, Sabat, I, and Attema, AE. Altruism and the link to pro-social pandemic behavior. *Front Health Serv*. (2022) 2:871891. doi: 10.3389/frhs.2022.871891
39. Pfattheicher, S, Nielsen, YA, and Thielmann, I. Prosocial behavior and altruism: a review of concepts and definitions. *Curr Opin Psychol*. (2022) 44:124–9. doi: 10.1016/j.copsyc.2021.08.021
40. Cohen, S, and Wills, TA. Stress, social support, and the buffering hypothesis. *Psychol Bull*. (1985) 98:310–57. doi: 10.1037/0033-2909.98.2.310
41. Cornwall J, Stringer MD. The wider importance of cadavers: Educational and research diversity from a body bequest program. *Anat Sci Educ*. (2009) 2:234–7. doi: 10.1002/ase.103

Annex A. Mapping of questionnaire items to COM-B dimensions

Questionnaire item	Target population	COM-B dimension	Rationale
Age, sex, education, occupation, place of residence	Donors	Capability (contextual)	Background factors shaping knowledge, literacy, and access to donation information.
How did you learn about body donation?	Donors	Opportunity	Reflects external sources of information and social exposure.
Did you find information easily?	Donors	Capability	Indicates perceived ability to access and understand relevant resources.
What motivated you to donate your body to science?	Donors	Motivation	Captures altruistic, symbolic, pragmatic, or gratitude-based determinants.
Have you discussed your decision with relatives?	Donors	Opportunity / Motivation	Social context and interpersonal validation of the decision.
What were their reactions?	Donors	Opportunity / Motivation	Influence of social environment on decision-making and persistence.
Why did you choose the University of Liège?	Donors	Opportunity	Institutional accessibility, proximity, or perceived reputation.
Do you have specific expectations for your family?	Donors	Motivation	Anticipated outcomes for relatives (compassion, respect, continuity).
Has your family influenced your decision?	Donors	Opportunity / Motivation	Family dynamics as social facilitators or barriers.
How should the population be made more aware?	Donors	Opportunity	Suggested strategies for enhancing societal awareness.
Were you aware of your relative's decision?	Families	Opportunity	Transmission of the decision within the family context.
Did you know their motivations?	Families	Motivation	Understanding the symbolic or altruistic drivers of the donor.
Do you think the donor's motivations were respected?	Families	Motivation	Evaluation of program alignment with donor's wishes.
How did you experience this bereavement?	Families	Capability / Motivation	Personal coping ability and emotional response.
Do you think grieving is different with body donation?	Families	Motivation	Perception of specific emotional challenges tied to donation.
Is there a way to ease this grieving process?	Families	Opportunity	Suggestions for institutional or social support.
How much time elapsed between death and restitution?	Families	Opportunity	Structural/institutional factor affecting family experience.
Was this waiting period reasonable?	Families	Motivation	Evaluation of satisfaction and acceptability of program logistics.
Were you informed about the restitution?	Families	Opportunity	Communication and transparency from the institution.
What type of funeral was carried out?	Families	Opportunity	Reflects cultural and logistical continuity after donation.
Were you satisfied with the body donation service?	Families	Motivation	Overall evaluation of program quality and respect.
What advice would you give to improve our services?	Families	Opportunity / Motivation	Concrete proposals for change and expectations toward the institution.

Annexe 2 : Tableau récapitulatif

Etudes	Niveau d'analyse	Objectif	Population et contexte	Variables clés	Types de données	Résultats principaux détaillés	Type d'analyses	Apport à la thèse
Etude 1 : Projet d'article	Niveau structurel	Comparer l'effet des modalités pédagogiques (haptique vs virtuel ; actif vs passif)	Étude multicentrique (Belgique vs RDC) Étudiants en médecine (n ≈ 943) Contextes contrastés (ressources élevées vs limitées)	Modalité (haptique/virtuel) interactivité (active/passive) contexte institutionnel	- Performance disciplinaire - Aptitudes visuospatiales (MRT) - Compétences numériques (ICNA)	- Effets significatifs des modalités sur les performances, mais fortement dépendants du contexte - Interaction modalité × contexte : efficacité variable selon Belgique vs RDC - Effets différenciés selon le type de compétence : → gains plus marqués en visuospatial qu'en connaissances factuelles - Interactivité active associée à de meilleures performances , mais seulement dans certains contextes pédagogiques - Rôle modulateur des compétences numériques (ICNA) : les étudiants les plus	-Alpha de Cronbach -ANOVA à un facteur -ANOVA factorielle -Tests post hoc de Tukey -Régression linéaire multiple / ANCOVA -Cohen's d	Montre que les effets des dispositifs ne sont ni universels ni transférables sans adaptation contextuelle

						compétents bénéficient davantage des modalités virtuelles		
						- Variabilité interindividuelle importante , suggérant des effets liés aux profils d'apprenants		
Etude 2 : Article 1 (ICNA – validation). Soumis dans ASE	Niveau individuel	Développer et valider une échelle de compétences numériques en anatomie	Étude multicentrique Belgique (ULiège), RDC (UNILU), HEPL Étudiants en santé (n ≈ 774) Contextes pédagogiques et technologiques contrastés	- Valeur motivationnelle du numérique, usages institutionnels, -Dispositions psychosociales, -Compétence numérique perçue, -distance critique vis-à-vis des technologies	- Questionnaire ICNA	- Structure factorielle multidimensionnelle validée, reflétant des compétences numériques disciplinaires et situées - Qualité psychométrique satisfaisante (cohérence interne, validité structurelle) - Différences significatives entre institutions : → niveaux plus élevés en Belgique qu'en RDC → forte hétérogénéité intra-contextuelle - Corrélations positives avec auto-efficacité et motivation, suggérant un lien entre compétences numériques et engagement académique	-Test de Bartlett -Indice KMO (Kaiser-Meyer-Olkin) - Analyse factorielle exploratoire (AFE / EFA) -Rotation oblimin -Analyse factorielle confirmatoire (AFC / CFA) -Alpha de Cronbach -Oméga de McDonald -ANOVA one-way -Tests post hoc de Tukey -Correction de Benjamini-Hochberg (FDR) -Cohen's d	Montre que les compétences numériques sont un déterminant structurant, inégalement distribué et contextuellement construit

						- Identification de profils différenciés d'étudiants selon leur niveau de compétence numérique - Mise en évidence que les compétences numériques sont dépendantes des opportunités pédagogiques et du contexte de formation		
Etude 3 : Article 2 (ARanatomy). Publié dans MORPHOLOGIE	Niveau procesuel	Analyser l'usage réel d'un environnement immersif et ses effets sur l'apprentissage	Étude multicentrique (Europe / Afrique) 5 cohortes, 3 institutions Étudiants en médecine, biomédical, hygiéniste buccodentaire (n = 2031) Intégration pédagogique hétérogène + versions d'outil évolutives	Intensité d'usage, type d'usage, motivation, version de l'outil, contexte pédagogique	-Perception (WBLT: learning, design, engagement) - Motivation (SDT) - Learning analytics (traces d'usage) - Performance (selon cohortes)	- Variabilité majeure des perceptions selon les cohortes , traduisant un effet dominant du contexte pédagogique - Aucune différence significative d'engagement entre utilisateurs et non-utilisateurs , indiquant un effet limité de l'exposition seule - Effet positif significatif sur les compétences visuospatiales chez les utilisateurs ($\approx 41.4\%$ vs 31.7% , $p < .05$) - Absence d'effet sur la performance académique immédiate (histologie)	-Analyses descriptives -ANOVA -Test t de Student -Analyses de corrélation -K-means clustering (k = 3)	Montre que l'effet des technologies dépend de leur appropriation réelle (usage), et non de leur simple présence

					- Corrélation positive entre intensité d'usage et performance visuospatiale ($r \approx 0.29-0.30$) - Mise en évidence d'une relation dose-effet entre profondeur d'usage et apprentissage - Motivation intrinsèque et émotions positives associées à un usage plus intense, tandis que l'amotivation est négativement liée à l'engagement - Identification de profils d'usage (faible, modéré, intensif) via clustering - Effets dépendants de : → maturité ergonomique de l'outil → qualité de l'intégration pédagogique		
--	--	--	--	--	---	--	--