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Neurocognitive outcomes of reinforced representational modelling in anatomical learning: The role of executive functions

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ABSTRACT

Purpose: This study examined neurocognitive outcomes of an innovative teaching approach in undergraduate anatomical education, focusing on executive functions with emphasis on cognitive flexibility. Reinforced representational modelling was implemented to assess its potential to support learning processes.
Methods: A quasi-experimental study involved first-year anatomy students from two universities (n = 116). Each institution delivered a single 30-hour program with different teaching methods: conventional lectures using 3D atlases and standard drawing tasks (control group) versus reinforced representational modelling (experimental group), taught by its regular instructor and aligned with its syllabus. Pre- and post-intervention outcomes were assessed using psychometric instruments: the Webexec scale for perceived executive difficulties and the Cognitive Flexibility Scale for cognitive flexibility. Statistical analyses included independent-samples t-tests, repeated-measures factorial ANCOVAs (time × treatment), and effect size estimations (Cohen's d, partial η^2).
Results: Perceived executive difficulties showed a strong time effect across both groups ($F(1) = 20.28$, $p < 0.001$, $\eta^2p = 0.176$), increasing over the course, whereas no treatment effect appeared after controlling for baseline differences. Cognitive flexibility was higher in the experimental group at post-test ($p = 0.044$, Cohen's $d = 0.36$), although this advantage diminished once covariates were controlled.
Conclusions: Reinforced representational modelling may foster flexible learning strategies in anatomy education. Cognitive flexibility showed some responsiveness to the intervention, while increases in perceived executive difficulties likely reflect the cognitive demands of early anatomy learning. Although effects were modest and partly influenced by covariates and baseline differences, findings suggest that executive functioning remains a key neurocognitive determinant in anatomical learning.

1. Introduction

1.1. Theoretical background

In the learning of anatomy, the modelling of students' mental representations of human structures and their functional relations plays a central role. An effective anatomy curriculum depends on how learners construct, revise and stabilise these representations, since anatomical understanding develops through the progressive refinement of structural and functional models. To move beyond rote memorisation, teaching strategies need to promote not only accuracy but also flexibility in the ways students represent and revise anatomical knowledge. Within this context, drawing and representational modelling offer opportunities for students to externalise, compare, and refine their mental models through iterative cycles of observation, reflection, and revision. These processes can foster forms of flexible thinking often associated with creativity, defined as the ability to generate novel associations and perspectives when addressing open-ended, unstructured, and multifaceted problems (Guilford, 1962). In anatomy, the relevance of these processes stems from the representational demands inherent in visualising spatial relations, correcting misconceptions, and integrating multiple viewpoints. The Observe–Reflect–Draw–Edit–Repeat (ORDER)

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method exemplifies this approach, providing a structured representational cycle that supports the progressive refinement of anatomical models (Backhouse et al., 2017).

In this sense, representational modelling can be understood less as an exercise in artistic creativity and more as a scaffold for cognitive flexibility. Modelling fosters flexible forms of knowledge that extend beyond static memorization (Clement, 2000), positioning models as representations of phenomena designed to describe or explain processes and thereby establishing modelling as a central practice in science education (Gilbert et al., 2000). More recently, Oliva (2019) emphasised that such models should be progressively constructed by students themselves, allowing them to refine and adapt their mental representations in interaction with new evidence or peer feedback.

Cognitive flexibility, in turn, is a core executive function that enables individuals to adapt to complex tasks, switch perspectives, and respond effectively to new or dynamic contexts (Ionescu, 2012; Yu et al., 2019), and it is particularly relevant for anatomy learning. Alongside working memory and inhibition, it forms part of the set of global executive functions support planning, problem-solving, and sustained attention (Diamond, 2013). These processes are known to be critical in education (Diamond, 2013) and have been linked to school readiness (Blair and Razza, 2007; Morrison et al., 2010), academic achievement (Borella et al., 2010; Duncan et al., 2007; Gathercole et al., 2004), and occupational success (Bailey, 2007). While working memory supports the temporary maintenance of verbal and visuospatial information, and inhibition enables the suppression of irrelevant responses (Diamond, 2013), anatomy learning requires a more dynamic cognitive process: learners must continually revise, reorganise, and update their mental models as they encounter new representations, correct misconceptions, and integrate additional spatial relationships. Cognitive flexibility is what enables this representational reconfiguration, allowing learners to shift between perspectives, reconcile alternative explanatory models, and adjust their understanding when discrepancies arise between their prior conceptions and the scientific model –a process well documented in research on model-based learning, understood as a progression from intuitive to more scientific models (Clement, 2000). Such discrepancies commonly prompt students to evaluate and revise their mental models (Gobert and Buckley, 2000). As learners progress from recognising isolated anatomical elements to developing relational and functional understanding, they rely increasingly on this capacity for flexible representational thinking.

These processes do not unfold uniformly across learners. Variability in executive functioning may reflect the "unity and diversity" of these cognitive processes, as research has shown that they comprise both shared and separable components across individuals (Friedman and Miyake, 2017). Such variability may influence how students engage with spatial complexity, revise mental models, and learn anatomy. Recognising this diversity aligns with equity and inclusion perspectives that emphasise accommodating heterogeneous cognitive profiles in scientific learning environments.

Although cognitive flexibility has been examined in other domains, such as in mathematics education (Sugilar and Nuraida, 2022), its role in anatomy remains underexplored. Existing studies show that drawing tasks can foster cognitive flexibility by encouraging students to revise and refine their anatomical representations as understanding develops (Pickering, 2015). Such activities demand detailed planning to depict structures accurately and the willingness to modify drawings iteratively as comprehension evolves, thereby supporting the detection and correction of misconceptions –a process central to constructing accurate anatomical models (Van Meter, 2001; Gómez Llombart and Gavidia Catalán, 2015). Analyses of students' drawings in anatomy have identified recurrent errors such as missing or mislocated structures, incorrect spatial relations between organs, and representations of systems as fragmented or poorly connected (e.g., linear digestive tracts ending in a "bag-like" stomach or incorrect organ linkages) (Banet and Núñez, 1988; Benedito, 1988; Reiss and Tunnicliffe, 2001; Cardak, 2015). By externalising these representations, drawing makes such difficulties visible and open to revision. Through this iterative process, drawing-based representational modelling further engages learners in selecting, organising, and integrating structural information, processes that promote scientific reasoning and the continual refinement of anatomical understanding (Schmeck et al., 2014; Ainsworth et al., 2011; Van Meter and Garner, 2005). Within the ORDER framework, successive cycles of observation, drawing, and revision support the gradual correction of these errors and the consolidation of increasingly integrated anatomical models (Backhouse et al., 2017). Moreover, drawing contributes to the development of the visuospatial abilities required in anatomy, enhancing spatial reasoning (Naug et al., 2016; Uttal et al., 2013) and the mental rotation skills essential for visualising structures across planes and orientations (Barger, 2016).

These spatial and representational demands become even more salient when students work with three-dimensional anatomical forms, a context in which cognitive flexibility is particularly critical (Ebersbach and Hagedorn, 2011). In this regard, approaches that deepen perceptual engagement with three-dimensional structures further support these processes: multisensory methods that integrate touch, sight, and drawing enhance perceptual comprehension and memory of 3D anatomical forms (Shapiro et al., 2020), while drawing directly onto 3D anatomical models provides an engaging, inclusive, and effective means of strengthening learners' spatial understanding (Horne et al., 2024).

From a psychological perspective, drawing has long been regarded as a reflection of representational change and flexibility in childhood (Karmiloff-Smith, 1992; Spensley and Taylor, 1999; Zhi et al., 1997). These findings underscore the tight link between drawing, representational adaptation, and executive functioning. Other studies (Panesi and Morra, 2021, 2018, 2016) could also be noted, as they suggest that the early development of flexibility in drawing is influenced by executive functions, independently of age, motor coordination, or drawing skill.

Taken together, this evidence highlights executive functions –and cognitive flexibility in particular– as key for anatomical learning. Core tasks, such as revising models, integrating spatial and functional relations, and reconciling alternative explanations, rely on learners' ability to flexibly reorganise mental representations. This connection provides a clear rationale for exploring whether representational modelling approaches, such as ORDER, may influence these executive processes within early anatomy curricula.

1.2. Study rationale and objectives

Against this background, the present study aimed to address the gap regarding the role of executive processes in anatomy education. Although anatomy learning involves high cognitive load, multiple representations, and continuous adaptation, little is known about how these demands affect executive functioning and, specifically, cognitive flexibility.

To examine this issue, we implemented reinforced representational modelling through a gamified version of the ORDER method (Backhouse et al., 2017). In this study, representational modelling was reinforced through two complementary mechanisms: (1) the iterative cognitive scaffolding inherent to the ORDER cycle, which progressively strengthens students' representational models; and (2) motivational–behavioural reinforcement using ClassDojo points and structured teacher feedback, designed to support sustained engagement and representational decision-making.

Two outcomes were assessed: perceived executive difficulties, as an indicator of global executive functioning, and cognitive flexibility, considered separately due to its theoretical and empirical relevance for representational learning. The inclusion of cognitive flexibility as a separate outcome was intended to provide a more precise interpretation of neurocognitive processes in anatomy learning. By addressing this question, the study highlights the relevance of neurocognitive processes in the acquisition of anatomical knowledge and opens new pathways for

designing curricula grounded in neuroscience-informed didactics.

Executive functions vary widely among undergraduate learners, reflecting the neurocognitive diversity that characterises student populations. Such diversity is increasingly recognised as a critical factor in anatomical education, since differences in executive functioning can affect students' capacity to process spatial relations, integrate complex information, and adapt to novel tasks. By focusing on executive functioning with an emphasis on cognitive flexibility, this study addresses this dimension of diversity and evaluates whether reinforced representational modelling may provide a more inclusive and neurocognitively informed pedagogical framework.

2. Materials and methods

2.1. Study design

A quasi-experimental pretest/post-test design was applied, involving one experimental group and one control group, each belonging to a different Spanish public university. This configuration reflects a natural experiment, preserving the ecological validity of authentic classroom conditions.

Although the two groups were embedded in their institutional contexts, several measures were taken to ensure comparability between them, including the alignment of course duration (30 h), semester timing, general anatomical foundations (terminology, anatomical position, axes, planes), and assessment schedule (identical pre- and post-tests administered simultaneously).

The independent variable was the instructional method (ORDER-based representational modelling versus conventional lecture-based teaching). The dependent variables comprised perceived executive difficulties (PED), serving as an indicator of global executive functioning, and cognitive flexibility (CF), both assessed through psychometric instruments (see 2.4 Instruments).

The study lasted seven weeks during the first semester of the academic year and was embedded in the regular human anatomy curriculum at each institution. Ethical approval was granted by the Clinical Research Ethics Committee of Aragón, Spain (PI22/383, September 7, 2022).

2.2. Participants

A total of 205 first-year undergraduate students enrolled in anatomy courses were invited to participate. Of these, 116 students completed both pre- and post-intervention measures and were included in the final analyses: 60 from the University of Zaragoza (experimental group; 14 women, 46 men) and 56 from the University of Lleida (control group; 13 women, 43 men). The mean age of the sample was 19.0 years (SD = 1.96).

Students who did not complete both assessments or did not attend the full instructional program were excluded (n = 89). Participation was voluntary, and informed consent was obtained from all participants prior to the start of the study.

2.3. Instructional programs

2.3.1. Curricular contents

Both interventions were integrated into first-year, first-semester anatomy courses and shared a common core of general anatomical foundations, including terminology, anatomical position, axes, and planes.

In addition to this common content, and in accordance with each institution's curriculum, during the intervention period the experimental program addressed multiple organ systems (circulatory, respiratory, digestive, excretory, reproductive, endocrine, nervous), with an explicit focus on their structure and function. The musculoskeletal system was not included in the experimental intervention, as it is covered in a later curricular block at that institution.

Likewise, in addition to the same general anatomical foundations, the control program focused on the musculoskeletal system during this period, including osteology, arthrology, and myology of the upper limbs, trunk, and lower limbs. Other organ systems were not part of the control intervention, as they are addressed in separate curricular units.

In both settings, teaching relied on 3D anatomical atlases and physical anatomical models, which constitute the standard resources for first-year, first-semester anatomy at both institutions.

2.3.2. Experimental condition

The experimental group (University of Zaragoza) attended a 30-hour program based on the Observe–Reflect–Draw–Edit–Repeat (ORDER) method (Backhouse et al., 2017), adapted through reinforced representational modelling. The sequence comprised observation of anatomical structures with visual prompts (Fig. 1) –such as 3D atlases, physical anatomical models, and augmented reality tools–, guided reflection, individual anatomical drawings (Fig. 2), collaborative group editing, and iterative redrafting at home (Fig. 3).

Reinforcement was provided during tasks through ClassDojo's point-based system and structured teacher feedback, both aimed at strengthening flexible representational thinking. ClassDojo points were awarded according to predefined behavioural categories, reinforcing sustained attention, continuous work, collaborative teamwork, autonomous study habits, and effort in anatomical drawing. Points were linked to engagement and process-related behaviours rather than accuracy, serving to maintain students' involvement during representational modelling tasks.

2.3.3. Control condition

The control group (University of Lleida) received a 30-hour conventional lecture-based program reflecting standard institutional practice. Instruction consisted of lectures supported by 3D anatomical atlases, note-taking, and tracing of drawings. Drawing tasks did not follow the ORDER sequence or representational modelling, and no reinforcement strategies were included. In addition, the control group used bone specimens when studying musculoskeletal content.

2.4. Instruments

Two psychometric instruments were employed: the Webexec (Buchanan et al., 2010; Morea and Calvete, 2020), and the Cognitive Flexibility Scale (CFS) (Martin and Rubin, 1995). Both instruments

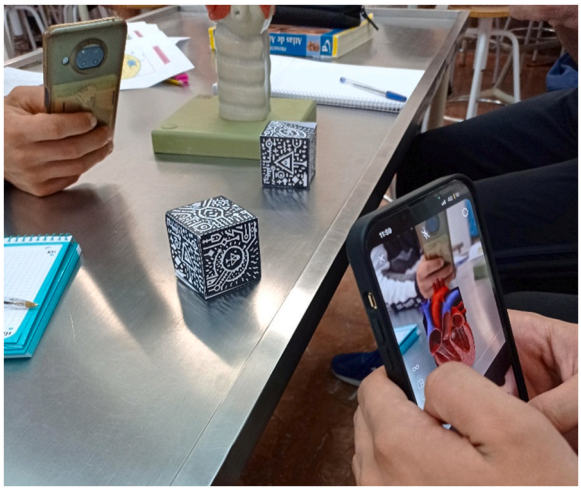

Fig. 1. Observation phase supporting initial mental-model construction: students inspecting a 3D augmented-reality heart to encode spatial and functional relations.

Fig. 2. Early representational output reflecting model revision: initial notebook sketches of the heart, including chamber configuration and corrected vessel trajectories.

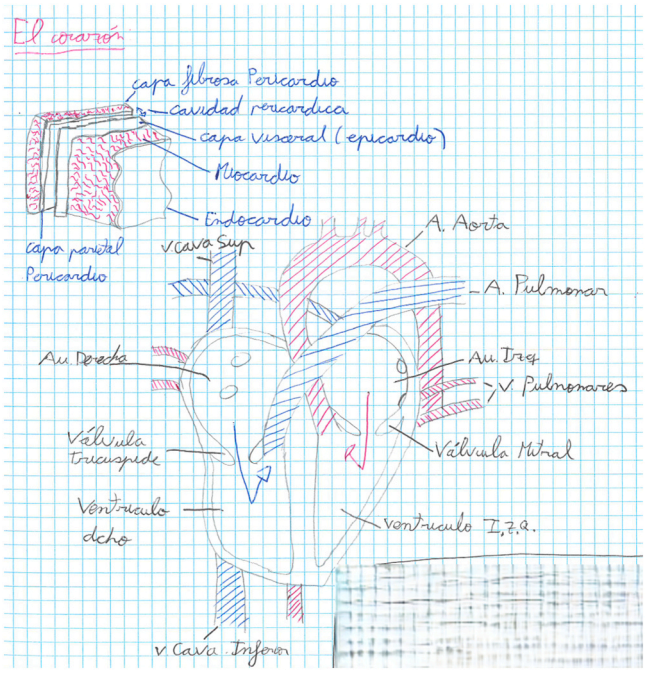

Fig. 3. Iterative refinement of representational models: final redrawn heart after the ORDER cycle, showing enhanced structural integration and improved representational coherence.

provide behavioural indicators of neurocognitive functioning.

Self-reported executive difficulties were assessed with the Webexec scale, consisting of six items scored on a 4-point scale (1 = very few problems, 4 = many problems). The Webexec captures everyday manifestations of executive functioning –such as planning, sustained attention, organisation, and task monitoring– through students' self-reported difficulties. Higher scores reflect greater perceived executive difficulties, which are known to influence learning in high-load subjects such as anatomy. Internal consistency in the present sample was acceptable (Cronbach's $\alpha = 0.741$; McDonald's $\Omega = 0.745$).

Cognitive flexibility was assessed with the CFS. The CFS is theoretically grounded in three core components of cognitive flexibility (Martin and Rubin, 1995): (1) the awareness that multiple alternatives or options are available in a given situation, (2) the willingness to adapt one's thinking or behaviour to changing demands, and (3) the perceived ability to behave flexibly when needed. Although these components are not scored as separate subscales, they inform the interpretation of the overall score, which reflects a dispositional tendency toward flexible thinking and behavioural adaptation. This scale evaluates an individual's tendency to shift perspectives, adapt to new information, and revise interpretations when demands change, offering a behavioural indicator of representational adaptability relevant to anatomy learning. Higher scores indicate a stronger dispositional capacity for flexible thinking, a process closely linked to model revision, spatial reasoning, and the integration of multiple anatomical representations. The original scale consists of 12 items rated on a 6-point Likert scale (1 = strongly disagree, 6 = strongly agree), of which four are reverse scored. A reliability analysis was conducted using Cronbach's alpha prior to the main analyses. Three items (items 2, 5, and 10), all belonging to the reverse-scored subset, were removed in order to achieve acceptable internal consistency. The final version included 9 items, with one reverse-scored. Internal consistency indices for the reduced scale were satisfactory (Cronbach's $\alpha = 0.754$; McDonald's $\Omega = 0.714$).

In addition to the main outcomes, several potential covariates were recorded, including sex, prior academic performance, study preferences (images vs. text), previous anatomy courses, previous experiences with drawing (excluding artistic training), perceived drawing competence, and drawing-related study habits.

2.5. Procedure

Baseline assessments were administered at the beginning of the semester (September 2022), before the implementation of the instructional programs. After the seven-week intervention, the same measures were re-administered (November 2022). All questionnaires were completed online. Data collection took place during scheduled class sessions and under the supervision of the course instructors to ensure compliance and reduce missing responses. Participation was voluntary, and students were informed that their responses would be treated anonymously and used solely for research purposes.

2.6. Statistical analysis

Cases with incomplete data (pre- or post-test only) were excluded from the analyses. Data were screened for normality and homogeneity, and outliers were removed prior to the final analyses. Baseline differences between groups were examined using independent-samples *t*-tests. Post-intervention differences were analysed with independent-samples *t*-tests and ANCOVA, controlling for baseline scores and significant covariates. Only covariates showing significant associations with the dependent variables were included in the models, which were tested separately for perceived executive difficulties and cognitive flexibility.

To investigate changes across the intervention, 2×2 repeated-measures factorial ANOVAs and ANCOVAs were conducted, with time (pre- vs. post-test) as the within-subjects factor and treatment (experimental vs. control) as the between-subjects factor. This approach enabled the assessment of the main effects of time and treatment, as well as their interaction. In addition, repeated-measures ANOVAs were conducted separately within each group only when a significant main effect of time was detected, in order to examine within-group changes across the intervention.

Effect sizes were reported as Cohen's d for mean comparisons and partial eta-squared (η^2p) for ANCOVA and ANOVA models. Conventional benchmarks were used as approximate guides (Cohen, 1988; Richardson, 2011): small ($d \geq 0.20$; $\eta^2_p \geq 0.0099$), medium ($d \geq 0.50$; $\eta^2_p \geq 0.0588$), and large ($d \geq 0.80$; $\eta^2_p \geq 0.1379$). The significance threshold was set at $p \leq 0.05$. All statistical analyses were carried out using IBM SPSS Statistics (version 26.0).

3. Results

3.1. Descriptive statistics and baseline analysis

Descriptive values (means ± SD) for each variable and group are shown in Table 1, after removal of extreme outliers. No baseline differences were observed for cognitive flexibility (CF; $p = 0.681$). In contrast, perceived executive difficulties (PED) were significantly higher in the control group compared with the experimental group ($t(100) = 2.726$, $p = 0.008$, MD = 1.06, 95 % CI [0.289, 1.834]), with a medium effect size ($d = 0.524$).

3.2. Perceived executive difficulties (PED)

A post-intervention *t*-test for independent samples indicated that the experimental group reported lower PED scores than the control group ($t(100) = 2.092$, $p = 0.039$, MD = 0.90, 95 % CI [0.046, 1.755]), with a small effect size ($d = 0.408$). Notably, this effect size was smaller than the baseline difference between groups, suggesting that the magnitude of between-group differences diminished over time.

An ANCOVA controlling for baseline scores revealed no significant group differences in the post-test ($p = 0.423$). When relevant covariates were included (study preference between images or text, prior academic performance, and football practice), the result remained non-significant ($p = 0.513$). None of these covariates were significant predictors in the adjusted model ($p = 0.521$, $p = 0.564$, and $p = 0.085$, respectively).

A repeated-measures factorial ANOVA demonstrated a significant main effect of time on PED ($F(1100) = 28.647$, $p < 0.001$, MD = 1.10, 95 % CI [0.692, 1.507]), with a large effect size ($\eta^2p = 0.223$). PED scores increased significantly from baseline to follow-up in both groups. The time effect was significant in the control group ($F(1,51) = 16.113$, $p < 0.001$, MD = 1.019, 95 % CI [0.509, 1.529], $\eta^2p = 0.240$) and in the experimental group ($F(1,49) = 13.152$, $p = 0.001$, MD = 1.180, 95 % CI [0.526, 1.834], $\eta^2p = 0.212$). The analysis also demonstrated a significant main effect of treatment ($F(1100) = 7.622$, $p = 0.007$, MD = 0.981, 95 % CI [0.276, 1.686]), with a small effect size ($\eta^2p = 0.071$). No significant interaction effect was observed ($p = 0.696$).

When covariates were considered, prior academic performance emerged as significant ($p = 0.041$). Under this model, the main effect of time remained significant ($p < 0.001$, $\eta^2p = 0.232$), but the treatment effect was no longer significant ($p = 0.063$). Study preference (images vs. text) and football practice were not significant predictors ($p = 0.200$ and $p = 0.123$, respectively).

Overall, PED scores increased significantly in both groups with large effect sizes, reflecting the cognitive demands of anatomy learning. Group differences at post-test were reduced compared with baseline, and no robust treatment effect was confirmed once covariates were included.

Table 1
Comparison of variables between experimental and control conditions.

Variables	Experimental Condition		Control Condition	
	Baseline	Follow-up	Baseline	Follow-up
Perceived Executive Difficulties	9.90 ± 1.90 (n = 50)	11.08 ± 2.08 (n = 50)	10.96 ± 2.03 (n = 52)	11.98 ± 2.26 (n = 52)
Cognitive Flexibility	33.53 ± 6.50 (n = 60)	35.83 ± 4.69 (n = 60)	33.04 ± 6.43 (n = 55)	33.96 ± 5.15 (n = 55)

Note. Data are presented as Mean ± Standard Deviation (n = number of participants after eliminating outliers). Sample sizes vary slightly across cells due to variable-wise removal of extreme outliers identified through SPSS stem-and-leaf plots.

3.3. Cognitive flexibility (CF)

A post-intervention *t*-test for independent samples showed higher CF scores in the experimental group compared with the control group ($t(110) = 2.04$, $p = 0.044$, MD = 1.87, 95 % CI [0.05, 3.69]), with a small effect size ($d = 0.36$).

An ANCOVA controlling for pre-test scores indicated significant group differences in the post-test CF scores ($F(1) = 3.96$, $p = 0.049$, MD = 1.85, 95 % CI [0.003, 3.69]), with a small effect size ($\eta^2_p = 0.034$, $R^2 = 3.6$ %). When significant covariates –prior academic performance ($r = 0.20$, $p = 0.034$) and sports practice ($\tau = 0.183$, $p = 0.022$) – were included alongside pre-test scores, the ANCOVA showed no significant group differences ($p = 0.140$). In this model, prior academic performance accounted for 7 % of the variance ($p = 0.004$, $R^2 = 10.6$ %) with a medium effect size ($\eta^2_p = 0.073$).

The repeated-measures factorial ANOVA (time × treatment) indicated a significant main effect of time ($F(1) = 3.96$, $p = 0.049$, MD = 0.91, 95 % CI [0.005, 2.14], $\eta^2p = 0.034$). This time effect was significant in the experimental group ($F(1) = 4.23$, $p = 0.044$, MD = 1.53, 95 % CI [0.04, 3.03], $\eta^2_p = 0.068$), but not in the control group ($p = 0.443$). A treatment effect was also observed ($F(1) = 5.64$, $p = 0.019$, MD = 2.58, 95 % CI [0.43, 4.74], $\eta^2p = 0.048$), although this effect disappeared when the prior academic performance was included as a covariate ($p = 0.077$). No significant interaction effect between time and treatment was found ($p = 0.723$).

In summary, CF improved significantly over time only in the experimental group, with medium effect sizes. Nevertheless, when controlling for covariates –particularly prior academic performance–these improvements were no longer attributable to the instructional program.

4. Discussion

4.1. Perceived executive difficulties

In both groups, perceived executive difficulties increased significantly over time. Experimental students consistently reported lower difficulties than their peers in the control condition at follow-up, although this difference reflected pre-existing disparities at baseline rather than the instructional intervention itself. These findings suggest that the experience of learning anatomy, regardless of teaching method, heightens students' awareness of challenges associated with executive functioning.

This interpretation is consistent with the literature describing anatomy as one of the most demanding courses in health sciences education, requiring the assimilation of complex terminology, spatial reasoning, and large amounts of factual knowledge (Cheung et al., 2021). Perceived difficulty may also vary depending on the content studied: for example, more than 61 % of students in one study identified the nervous system as the most difficult topic, followed by the muscular system (13.1 %), while the cardiovascular and skeletal systems were rated as less challenging (Lieu et al., 2018). In the present intervention, the experimental group studied multiple systems, including the nervous system, whereas the control group focused on the musculoskeletal system. Exposure to particularly demanding content may therefore have amplified perceptions of executive difficulties, even if the overall level of perceived strain remained lower in the experimental group.

Overall, these results highlight that increases in PED are a robust outcome of anatomy learning itself, consistent across teaching methods. From a pedagogical standpoint, this underscores the importance of incorporating strategies that explicitly support executive functioning within anatomy curricula.

Evidence from cognitive load theory (Sweller, 2011) and frameworks such as Load Reduction Instruction (Martin, 2016; Martin and Evans, 2018) emphasises the value of scaffolding, structured practice, informative feedback, and adaptive task design (Evans et al., 2024; Martin

et al., 2021). Specific strategies such as concept mapping (Bolatli and Bolatli, 2024) or augmented reality (Küçük et al., 2016) have been shown to reduce extraneous load. Furthermore, teaching style plays a crucial role: autonomy-supportive approaches are more effective in sustaining motivation and engagement than controlling or overly demanding practices (Evans et al., 2024).

4.2. Cognitive flexibility

Cognitive flexibility improved significantly in the experimental group, with both treatment and time effects indicating greater sensitivity to pedagogical intervention than other executive functions. This improvement suggests that representational modelling through drawing may foster adaptive thinking processes essential for anatomy learning, as previous studies have demonstrated its role in promoting flexibility (Pickering, 2015), particularly when representing three-dimensional structures (Ebersbach and Hagedorn, 2011), as is the case in anatomical drawing. The iterative nature of the ORDER framework (Backhouse et al., 2017) –requiring students to edit and repeat their work– likely supported the progressive refinement of their mental models. These results are consistent with prior research showing that flexibility is a trainable function that can be enhanced through targeted practice (Diamond, 2013).

A broad consensus in the literature supports the link between cognitive flexibility and academic performance across cultures and educational levels. Adolescents' flexibility predicts better outcomes globally, particularly in contexts that emphasise adaptability and self-improvement (Zheng et al., 2024). In specific populations, such as children in institutional care, reduced flexibility has been associated with lower achievement, with task persistence mediating this effect (Sousa et al., 2023). At the university level, deep learning has been linked to higher performance and greater flexibility, whereas surface learning corresponds to poorer outcomes and reduced flexibility, although it may still predict exam grades in memory-focused contexts (Toraman et al., 2020). Flexibility is also associated with positive academic emotions, expectations of success, and reduced task avoidance (Hailikari et al., 2022), while neuroimaging studies demonstrate correlations between flexibility-related brain activation and academic performance in reading and mathematic (Nugiel et al., 2023).

Nevertheless, in the present study, the treatment effect on CF disappeared when prior academic performance was controlled, suggesting that individual differences in baseline achievement influenced the observed gains. This highlights that the intervention does not exert effects independently but interacts with learners' profiles. From a pedagogical perspective, this reinforces the interpretation of flexibility as an adaptive competence shaped by engagement and cultural context (Legare et al., 2018). Interventions in anatomy education may therefore benefit from being personalised to accommodate varying academic backgrounds, while fostering autonomy, reflection, and collaborative problem solving, as flexibility is closely tied to self-regulated learning in higher education (Orakcı, 2021). Creating a positive classroom climate is equally important, as students report learning more deeply and becoming more cognitively flexible in supportive environments (Toraman et al., 2020).

4.3. Implications for neurocognitive diversity and inclusive curricula in anatomy education

The present findings indicate that studying anatomy has a measurable influence on students' perceived executive difficulties, which increased across groups regardless of instructional method. At the same time, cognitive flexibility appeared more sensitive to the intervention, showing improvement in the experimental group through representational modelling. Although modest, these effects underscore the value of integrating representational practices into anatomy curricula, as such approaches may shape neurocognitive processes.

The outcomes varied according to students' profiles, with academic performance and other covariates moderating the effects. This highlights the significance of neurocognitive diversity in anatomy classrooms: learners do not always start from the same baseline nor respond uniformly to instructional methods. Recognising such diversity is necessary for designing equitable and inclusive curricula. Pedagogical strategies that incorporate iterative modelling may provide targeted support for students with distinct cognitive profiles, contributing to more accessible learning environments.

4.4. Limitations of the study and future directions

The study was conducted as a natural experiment, with the absence of randomisation representing a potential limitation of this design. In addition, the experimental and control groups belonged to different institutions, which may have introduced contextual differences beyond the instructional method itself, potentially contributing to the observed differences between groups, including teaching staff (e.g., differences in style, clarity, and engagement), learning environments, and curricular sequencing. Nevertheless, this approach made it possible to capture classroom reality under authentic conditions, with the heterogeneity and diversity of students, thereby providing strong ecological validity to the findings.

Baseline differences between groups on the analysed variables were controlled, and outliers were excluded, which strengthened the robustness of the analyses. For future research, however, it would be advisable to include diagnostic information on mental health conditions that may influence executive functioning, such as depression (Taylor Tavares et al., 2007), conduct disorders (Fairchild et al., 2009), and attention deficit hyperactivity disorder (Diamond, 2005; Lui and Tannock, 2007).

The study prioritised respecting the autonomy of each institution, which meant that evaluation criteria, grading procedures, and the content assessed in examinations differed across sites. Consequently, students' post-intervention grades were not included in the analysis, restricting the possibility of linking the intervention directly to subsequent academic performance. Similarly, because the research did not interfere with each institution's curriculum, the content addressed varied between sites, which may have introduced additional differences in students' cognitive load. Nevertheless, this variation reflects the authentic conditions of anatomy teaching across different university contexts, thereby enhancing both the ecological validity and the transferability of the findings.

Future work would also benefit from explicitly assessing cognitive load and comparing the present programme with approaches that integrate Load Reduction Instruction strategies, in order to test their combined impact on students' motivation, engagement, and executive functioning. Moreover, we propose that neurocognition be explicitly considered in curricular design as an expression of functional diversity. By acknowledging interindividual variability as a form of neurocognitive diversity, anatomy education can advance towards curricula scientifically rigorous and socially equitable.

5. Conclusions

The findings of this study suggest that anatomy learning exerts a measurable influence on students' executive functioning, with perceived executive difficulties increasing across groups regardless of the instructional method. At the same time, cognitive flexibility showed greater sensitivity to pedagogical intervention, with improvements observed in the experimental condition through reinforced representational modelling.

Although modest and partly moderated by individual academic profiles, these outcomes highlight the relevance of integrating iterative modelling practices into anatomy curricula. Such approaches may support content mastery and contribute to the development of adaptive cognitive processes essential for learning.

By situating executive functioning and cognitive flexibility within anatomy education, this study underscores the need to acknowledge neurocognitive diversity in university classrooms. Designing anatomy curricula that explicitly consider interindividual variability can foster learning environments that are scientifically rigorous, pedagogically effective, and socially equitable.

CRediT authorship contribution statement

Alejandro Quintas-Hijós: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lorena Latre-Navarro:** Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Institutional review board statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Clinical Research Ethics Committee of Aragón (Spain) (statement number: PI22/383, on September 7, 2022).

Ethical approval

The study received approval on September 7, 2022 (statement number: PI22/383) by the Ethical Committee of Clinical Research of Aragon (Spain).

Other disclosures

None

Disclaimers

None

Previous presentations

None

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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