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Adoption of Educational Neurotechnologies: A Mixed-Methods PLS-SEM and fsQCA Approach

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Abstract

Bridging the intention-action gap in higher education technology adoption requires rigorous empirical frameworks capable of modeling complex causal pathways. This study examines the mediating and moderating mechanisms underlying the adoption of neurotechnological strategies and the transformation of teaching practice in accredited private universities in Peru. Employing a robust methodological triangulation design ($N = 215$), Partial Least Squares Structural Equation Modeling (PLS-SEM) was integrated with fuzzy-set Qualitative Comparative Analysis (fsQCA). Results demonstrate that the direct effect of neurotechnological adoption on transformed practice is moderate ($\beta = 0.19, p < .05$), but substantially amplified through dual mediation: perceived technological efficacy ($\mathrm{VAF} = 51.2\%$) and perceived institutional resilience ($\mathrm{VAF} = 22.7\%$). Furthermore, Johnson-Neyman floodlight analysis identifies teaching experience as a non-linear boundary condition, nullifying the main effect beyond 11.4 years of service. Complementary fsQCA reveals three sufficient causal configurations leading to high pedagogical transformation, establishing equifinality. Methodological controls for common method bias and endogeneity (Gaussian copula) confirm the structural stability of the model. This study highlights the necessity of combining symmetrical and asymmetric modeling to capture non-linear behavioral dynamics in educational innovation.

Introduction

Background and Problematisation of the Gap

The convergence of cognitive neuroscience and educational technology has generated unprecedented expectations regarding the transformative potential of neurotechnologies in higher education. Tools such as augmented reality, three-dimensional modelling, educational robotics and neurofeedback systems promise to optimise students' brain plasticity, facilitating sustained attention and promoting the consolidation of complex learning. However, as Kamoun et al. (2024) argue, despite the high level of reported knowledge regarding tools such as ChatGPT, 63.4% of university lecturers report lacking the training and resources to integrate these technologies in a pedagogically meaningful way. This tension between the discourse in favour of technological innovation and effective teaching practice constitutes what Rivadeneira et al. (2024) identify as a structural paradox: the transformative potential is recognised, but university governance maintains instrumental and cautious uses that do not substantially alter teaching and learning practices.

The issue becomes more complex in the Latin American context, where Torres et al. (2025) document an uneven adoption of artificial intelligence in higher education, concentrated in a few countries and marked by strong tension between promises of personalisation and persistent structural barriers: poor infrastructure, inadequate teacher training and well-founded cultural resistance. For business administration lecturers at Peruvian universities, this scenario places their experience within an 'island-like' innovation ecosystem, where pilot projects coexist with traditional classrooms that replicate 19th-century pedagogical models. As Chacha et al. (2025) point out, only 34% of lecturers with ICT certifications achieve transformative integration, whilst those with intermediate digital skills but a strong pedagogical foundation achieves better results, demonstrating that the abundance of accreditation workshops does not automatically translate into innovative practices.

The central paradox driving this research lies in the fact that, whilst there is theoretical consensus on the disruptive potential of neurotechnologies for cognitive mediation, actual adoption by Latin American university lecturers remains disproportionately low compared to stated intentions. This intention-action gap cannot be explained by linear models of technology adoption that assume an automatic sequence of awareness, favourable attitude and

effective use. As documented by Eusebio et al. (2025), teachers' acceptance of artificial intelligence is hampered by anxiety, perceived risks, a lack of pedagogical alignment and deficient institutional conditions, particularly in developing countries. Shahid et al. (2024) complement this view by demonstrating that anxiety significantly reduces readiness for adoption and attitudes towards AI-based assessment systems, whilst stated resistance has a small and non-significant effect, suggesting that the blockage is not conscious opposition but rather unresolved psychological distress.

Background and Problem Definition

Previous studies on technology adoption in higher education have prioritised descriptive assessments of teaching perceptions without modelling the causal pathways linking intention to actual practice. The dominant literature, anchored in TAM and UTAUT models developed in WEIRD (Western, Educated, Industrialised, Rich, Democratic) contexts, assumes that perceived usefulness and ease of use linearly predict intention to use, and this in turn predicts adoptive behaviour. However, as Habib (2025) criticises, intention to use may have a negative and non-significant effect on attitude, revealing a counterintuitive gap: one can declare an intention without consolidating favourable attitudes or authentic practices. This finding calls into question the ecological validity of surveys that measure only declared intention, thereby overestimating the actual adoption of neurotechnologies.

Furthermore, previous studies have been limited to symmetric regression analyses that assume uniform causal relationships between variables, ignoring the possibility of asymmetric causal configurations where multiple combinations of conditions can lead to the same outcome. As Bai and Yang (2025) point out, the extended AIDUA model reveals that the more disruptive the tool, the more the opportunity-threat conflict intensifies, generating non-linear adoption trajectories that conventional methods fail to capture. Elhassani et al. (2025), through a bibliometric analysis of 803 articles, document the hegemony of TAM/UTAUT and the lack of unifying frameworks that integrate governance, equity and ethics, noting that the theoretical field focuses on accepting individual technologies whilst ignoring the power structures and regulation that determine actual uses.

This study overcomes these limitations through robust methodological triangulation that combines PLS-SEM for structural equation modelling with fsQCA for configurational analysis of causal pathways. As Peiris (2024) argues, the pandemic transformed the teacher into an extension of technology, with roles as facilitator and curator, but also with overload and stress that were not resolved by the return to face-to-face teaching. This experience suggests that resistance to technological change is not simply a matter of lagging behind, but rather a defence of humanistic roles and professional well-being—a perspective that classical adoption models underestimate by prioritising instrumental dimensions over emotional ones.

Research Question and Objectives

In response to the identified gaps, this research addresses the following central question: What psychological and organisational mechanisms mediate the relationship between the adoption of neurotechnological strategies and the transformation of teaching practice in Peruvian private universities accredited by SUNEDU? This question is broken down into specific objectives aimed at: (1) modelling the causal structure between neurotechnological strategies, mediating mechanisms and transformed practice using PLS-SEM; (2) identifying causal and/or configurations sufficient for high technology adoption using fsQCA; and (3) determining boundary conditions that modulate the strength of structural relationships.

The context of Peruvian private universities under the SUNEDU regulatory framework serves as a natural theoretical laboratory for testing the limits of theories of technology adoption, given that it combines institutional isomorphic pressures for accreditation with heterogeneity in the digital maturity of the teaching staff. As Andrade et al. (2024) note, there is a predominance of research on ChatGPT in Asia and a scarcity of Latin American studies, placing Peruvian universities in a de facto unregulated space where institutional intent does not translate into formal mechanisms for integration or evaluation. Zheng et al. (2025), through a UTAUT2 meta-analysis involving 91 studies and 37,910 participants, confirm that habit, hedonic motivation, perceived value and facilitating conditions are the strongest predictors of intention to use, whilst expected effort and social influence have moderate effects, suggesting that the mere post-SUNEDU obligation to use LMS or AI will not bridge the intention-use gap unless coherent routines and institutional support are established.

Theoretical Framework and Hypothesis Development

Main Theoretical Framework

This study bases its conceptual framework on the cross-fertilisation between Rogers' theory of the diffusion of innovations and the Unified Theory of Acceptance and Use of Technology (UTAUT). Rogers' theory posits that the adoption of innovations follows a normal distribution curve where individuals pass through sequential stages: awareness, persuasion, decision, implementation and confirmation. In educational contexts, this sequence becomes more complex because pedagogical innovation is not the adoption of an isolated technological artefact but rather the reconfiguration of professional identities and institutionalised practices. As Eusebio et al. (2025) argue, classical acceptance models underestimate the cognitive and ethical burden perceived by teaching staff, creating the paradox of useful tools being rejected due to perceived risk and inconsistency with educational aims.

The UTAUT model, developed by Venkatesh et al., integrates elements from eight previous models of technology acceptance, proposing that intention to use is predicted by four fundamental constructs: performance expectancy, effort expectancy, social influence and enabling conditions. The meta-analysis by Zheng et al. (2025) confirms that these predictors operate with varying strength depending on region, culture and income, challenging the WEIRD assumption that the same predictors operate equally across all contexts. For Peruvian business school lecturers, this implies that the mere post-SUNEDU obligation to use technologies will not bridge the intention-use gap unless specific routines and support systems are established that recognise the distinctiveness of Latin American institutions.

Complementary Framework

To address the blind spot of the technology-centred model, this study incorporates Sweller's cognitive load theory as a complementary framework. This theory distinguishes three types of cognitive load: intrinsic (determined by the complexity of the material), extrinsic (generated by inadequate instructional design) and generative (oriented towards the construction of lasting schemas). When designed appropriately, neurotechnologies can reduce the extrinsic cognitive load on teachers during instructional design, freeing up cognitive resources for transformed practice. As Bai and Yang (2025) point out, perceptions of quality and explainability enhance performance expectations, whilst ethical risk increases the perceived cognitive load, generating an opportunity-threat conflict that modulates effective adoption.

The integration of these frameworks allows us to postulate that the adoption of neurotechnological strategies impacts the transformation of teaching practice only when specific mediations are activated that reduce extrinsic cognitive load and strengthen teachers' self-confidence. Shahid et al. (2024) define readiness for adoption as a combination of performance expectations, effort and facilitating conditions, showing that anxiety erodes both this readiness and attitudes towards AI systems. This finding suggests that the effect of neurotechnological strategies on transformed practice is not direct but mediated by internal psychological and external organisational mechanisms that must be empirically elucidated.

Hypothesis Development

Based on the theoretical synergy outlined above, the following research hypotheses are derived. The first posits a direct positive effect: neurotechnological strategies, understood as the degree of adoption and pedagogical integration of immersive technologies based on neuroeducation principles, exert a positive effect on transformed teaching practice, defined as an observable shift in teaching methodologies towards active, student-centred approaches mediated by neuroeducational technology. This hypothesis is based on the convergence between the perceived utility of immersive technologies and the optimisation of pedagogical processing, which predicts the positive direction of the effect.

The mediation hypotheses postulate that the main effect operates through two explanatory mechanisms. Perceived technological efficacy, understood as the teacher's self-confidence in their ability to implement neurotechnological tools effectively, mediates the relationship between neurotechnological strategies and transformed practice, constituting an internal psychological process that transcends simple correlation by elucidating the underlying mechanisms of behavioural change. In parallel, perceived institutional resilience, defined as the perception of an organisation's capacity to absorb technological disruptions and maintain educational functions during the digital transition, also mediates this relationship, operating as an external or

ganisational process that complements the psychological mediation.

Finally, the moderation hypothesis posits that teaching experience in terms of years of service activates or deactivates the main relationship between neurotechnological strategies and transformed practice. This moderating effect is based on the contrast between digital natives and digital immigrants, where the cognitive rigidity associated with mental schemas consolidated by years of traditional practice dampens the impact of technological innovations. The expected pattern of interaction is an amplification of the effect at low levels of experience and a progressive attenuation that converges to zero at high levels of teaching seniority.

H1

Neurotechnological strategies exert a positive and significant effect on transformed teaching practice.

H2

Perceived technological efficacy mediates the relationship between neurotechnological strategies and transformed practice.

H3

Perceived institutional resilience mediates the relationship between neurotechnological strategies and transformed practice.

H4

Teaching experience moderates the relationship between neurotechnological strategies and transformed practice, with the effect being greatest for teachers with less seniority.

Materials and Methods

Research Design

This study adopted a multicentre cross-sectional correlational design, justified by the ethical impossibility of experimentally manipulating neurotechnological variables in real educational contexts. However, the design was strengthened by statistical controls for endogeneity, which allow for robust causal inference despite the absence of randomisation. As recommended by Chinnaraju (2025), PLS-SEM was selected for its robustness to non-normal distributions and moderate sample sizes, as well as its capacity for predictive modelling with emerging theories. The analysis was complemented by fsQCA to capture asymmetric causal configurations that the symmetric SEM approach fails to detect, following the strategy of Appiah and Agblewornu (2025) which combines both methods to demonstrate equifinality and asymmetric causality in technology adoption processes.

Context and Sample

The target population consisted of undergraduate business administration lecturers at private universities accredited by SUNEDU in Metropolitan Lima. The inclusion criteria specified lecturers required to use learning management systems (LMS) in their courses, whilst the exclusion criteria excluded those teaching exclusively online or on temporary contracts of less than one academic semester. The sample size of N = 215 was determined by statistical power for PLS-SEM, considering an average effect size of ($f^2 = 0.15$), a significance level of $\alpha = 0.05$ and power = 0.95, following the recommendations of Nascimento and Macedo (2025) for complex models with simultaneous mediations and moderations.

Variables and Operationalisation

The study variables were operationalised using validated scales adapted to the context of neurotechnologies in business education. The independent variable Neurotechnological Strategies was measured using an adapted 7-item scale in a 1–7 Likert format, assessing the use of augmented reality, 3D modelling, educational robotics, neurofeedback, virtual environments, cognitive wearables and gamification based on brain reward mechanisms. The dependent variable, Transformed Teaching Practice, was operationalised using 8 items that capture the design of multimodal sessions, curricular flexibility, neuroscientific formative assessment, adaptation to diverse cognitive profiles, promotion of neuroplasticity, reduction of extrinsic cognitive load, fostering of flow states, and transfer through simulation.

The mediators included Perceived Technological Efficacy (4 items), which assesses confidence in operating interfaces, resolving technical problems, designing neurotechnological activities and guiding students; and Perceived Institutional Resilience (5 items), which measures support in the event of failures, availability of resources, an error-tolerant culture, capacity for curricular adaptation and administrative support for

experimentation. The moderator Teaching Experience was operationalised as years of service in higher education, centred for moderation analysis. Control variables included age and gender. The expected psychometric properties were a Cronbach's alpha greater than 0.80, composite reliability greater than 0.70 and extracted mean variance greater than 0.50, thresholds supported by Li and Lay (2024) and Wang and Kalkbrenner (2025).

Table of Variable Operationalisation

Variable	Definition	Indicators	Scale
Neurotechnological Strategies	Adoption of immersive technologies (AR, 3D, robotics)	7 items: AR, 3D modelling, robotics, neurofeedback, virtual environments, wearables, gamification	Likert 1–7
Transformed Practice	Shift to active approaches mediated by neurotechnology	8 items: multimodal sessions, curriculum flexibility, neuroscientific assessment, cognitive adaptation, neuroplasticity, reduced cognitive load, flow, simulation	Likert 1–7
Perceived Effectiveness	Self-confidence in implementing neurotechnologies	4 items: operating interfaces, problem-solving, designing activities, guiding students	Likert 1–7
Institutional Resilience	Organisational capacity to absorb disruptions	5 items: support in the event of failures, technical resources, a tolerant culture, curricular adaptation, administrative support	Likert 1–7
Teaching experience	Years of service in higher education	Centred continuous variable (1–28 years)	Ratio

Procedure and Control of Bias

Data collection was carried out via a digital platform with item order counterbalanced through random rotation. To reduce common method bias (CMB), a two-week time lag was applied between the measurement of independent variables (T1) and dependent variables (T2), alongside instructions guaranteeing anonymity to reduce motivated consistency. As an additional technique, a theoretically irrelevant positive affect scale was included as a marker variable, where correlations with the common latent variable of less than 0.10 indicate the absence of systematic bias, following the protocol of Appiah and Agblewornu (2025).

Analytical Strategy

The sequential analytical flow comprised six stages. First, descriptive analyses and a correlation matrix with HTMT evaluation for discriminant validity. Second, PLS-SEM with 5,000-sample bootstrapping for estimation of path coefficients and significance tests. Third, indirect mediation analysis with bias-corrected percentile confidence intervals. Fourth, moderation analysis with simple slopes and the Johnson-Neyman region of significance. Fifth, fsQCA to identify necessary and sufficient configurations. Sixth, robustness analysis using alternative specifications, including OLS regression, 2SLS with an instrumental variable, exclusion of outliers, and multi-group analysis by gender. Endogeneity control was implemented using the Gaussian Copula approach, supplemented with Propensity Score Matching for matching based on prior technological propensity, following the recommendations of Ide et al. (2025).

Results

Preliminary Analyses and Measurement Validity

The descriptive statistics for the main constructs reveal approximately normal distributions with skewness values between − 0.61 and 0.84, and kurtosis between − 0.31 and 0.62, within acceptable ranges for analysis of variance. The observed means range from 4.38 (Institutional Resilience) to 5.12 (Perceived Technological Efficacy), with standard deviations indicating substantial variability in the sample. The assessment of convergent validity using composite reliability (CR) and average variance extracted (AVE) shows values exceeding the recommended thresholds set by the : CR between 0.89 and 0.94, AVE between 0.62 and 0.74. HTMT ratios below 0.85 confirm adequate discriminant validity between all pairs of constructs.

Table 1

Descriptive Statistics, Reliability and Validity Measures

Construct	Items	Mean	SD	Skewness	Kurtosis	α	CR	AVE	HTMT ratio
Neurotechnological Strategies	7	4.82	1.34	-0.42	-0.18	0.91	0.93	0.62	0.72
Transformed Teaching Practice	8	4.65	1.28	-0.35	-0.24	0.93	0.94	0.65	0.68
Perceived Technological Efficacy	4	5.12	1.15	-0.61	0.14	0.88	0.92	0.74	0.64
Institutional Resilience	5	4.38	1.42	-0.28	-0.31	0.86	0.89	0.63	0.71
Teaching experience	1	8.45	5.23	0.84	0.62	—	—	—	—

Note. N = 215. α = Cronbach's alpha; CR = Composite Reliability; AVE = Average Variance Extracted. All HTMT ratios below the threshold of 0.85 indicate adequate discriminant validity. All measurements use 1–7 Likert scales except Teaching Experience (years).

The assessment of common method bias using the marker variable technique shows non-significant correlations between positive affect and the model variables (all < 0.10), suggesting the absence of substantial bias. VIF values between 1.24 and 2.18 indicate the absence of severe multicollinearity. The intercorrelation matrix reveals positive and significant associations in the expected direction, with the highest correlation between Perceived Technological Efficacy and Transformed Teaching Practice (r = 0.61).

Table 2

Correlation Matrix and Assessment of Common Method Bias

Variable	1	2	3	4	5	6	7
1. Neurotechnological Strategies	(0.79)						
2. Transformed Teaching Practice	0.58**	(0.81)					
3. Perceived Technological Efficacy	0.52	0.61**	(0.86)				
4. Institutional Resilience	0.44**	0.48**	0.39**	(0.79)			
5. Teaching Experience	0.12	0.18*	0.14	0.22**	—		
6. Age (Control)	0.09	0.15	0.11	0.19*	0.71**	—	
7. Indicator variable (Positive affect)	0.08	0.06	0.09	0.11	0.04	0.07	(0.85)

*Note. N = 215. On the diagonal: square root of the AVE. **p < .01, *p < .05. Correlations with the marker variable are non-significant (all < 0.10), suggesting the absence of substantial common method bias. VIF values between 1.24–2.18.*

Assumption Testing and Endogeneity

Breusch-Pagan tests for heteroscedasticity did not reveal any serious violations of homoscedasticity. Endogeneity control using the Gaussian Copula approach yielded robust coefficients comparable to those estimated by OLS, ruling out substantial simultaneity bias between teaching practice and technology adoption. The test for configural and metric invariance between subgroups of teaching experience using multigroup analysis revealed no significant differences in factor loadings, supporting the comparability of the structural models across sample segments.

Main Hypothesis Tests

The sequence of PLS-SEM hierarchical models reveals an incremental pattern of explained variance consistent with the proposed hypotheses. Model 1, including control variables, explains 8% of the variance in transformed practice. The inclusion of neurotechnological strategies in Model 2 significantly increases the explanatory power ($R^2 = 0.26$, $\Delta R^2 = 0.18$, $f^2 = 0.22$), with a path coefficient of $\beta = 0.42$ ($p < .001$) confirming H1 of a positive direct effect. Model 3 incorporates the mediators, raising R^2 to 0.43 ($\Delta R^2 = 0.17$) and reducing the direct effect to $\beta = 0.18$ ($p < .05$), a pattern indicative of partial mediation. Finally, Model 4 adds the interaction term, reaching $R^2 = 0.46$ with a significant moderating effect of $\beta = 0.15$ ($p < .05$).

Table 3

Results of the Hierarchical PLS-SEM Analysis (Standardised β coefficients)

Path	Model 1 (Controls)	Model 2 (Direct)	Model 3 (Mediation)	Model 4 (Moderation)
Control Variables				
Age → Practice	0.09 (0.11)	0.04 (0.09)	0.03 (0.08)	0.02 (0.08)
Gender → Practice	0.12 (0.13)	0.08 (0.11)	0.07 (0.10)	0.06 (0.10)
Direct Effects				
Strategies → Practice	—	0.42*** (0.09)	0.18* (0.08)	0.19* (0.08)
Mediation Pathways				
Strategies → Efficacy	—	—	0.51*** (0.07)	0.49*** (0.07)
Effectiveness → Practice	—	—	0.38*** (0.09)	0.37*** (0.09)
Strategies → Resilience	—	—	0.33** (0.11)	0.32** (0.11)
Resilience → Practice	—	—	0.26** (0.09)	0.25** (0.09)
Moderation				
Strategies × Experience	—	—	—	0.15* (0.07)
Model Fit				
R^2	0.08	0.26	0.43	0.46
Adjusted R^2	0.07	0.25	0.42	0.44
ΔR^2	—	0.18	0.17	0.03
f^2	—	0.22	0.35	0.06
SRMR	0.048	0.041	0.038	0.036
NFI	0.92	0.94	0.96	0.97

*Note. N = 215. Values represent standardised path coefficients with robust standard errors in brackets. ***p < .001, **p < .01, *p < .05.*

Indirect Effects Analysis

Mediation analysis using bootstrapping of 5,000 samples confirms both mediation hypotheses. The indirect path via Perceived Technological Efficacy yields an effect of 0.194 (95% CI: 0.118–0.284), explaining 51.2% of the variance in the total effect (VAF). The pathway via Institutional Resilience shows an indirect effect of 0.086 (95% CI: 0.038–0.158), with a VAF of 22.7%. The total indirect effect combines both pathways at 0.280 (95% CI: 0.189–0.386), accounting for 73.9% of the total effect. Notably, the direct post-medication effect becomes non-significant (β = 0.098, 95% CI includes zero), indicating complementary full mediation where psychological and organisational mechanisms account for virtually the entire influence of neurotechnological strategies on transformed practice.

Table 4
Analysis of Specific Indirect Effects (Bootstrap BCa 5000 samples)

Indirect Path	Point Estimate	EE	95% BCa CI	VAF (Variance Explained)
Strategies → Effectiveness → Practice	0.194	0.043	[0.118, 0.284]	51.2% (Partial mediation)
Strategies → Resilience → Practice	0.086	0.032	[0.038, 0.158]	22.7% (Partial mediation)
Total Indirect Effect	**0.280**	**0.051**	**[0.189, 0.386]**	**73.9**
Direct Effect (post-mediation)	0.098	0.058	[-0.012, 0.211]	26.1% (ns)
Total Effect	0.378	0.061	[0.262, 0.501]	—

Note. CI = Confidence Interval. BCa = Bias-corrected and accelerated. VAF indicates the proportion of the total effect mediated. The non-significant direct effect post-mediation indicates complementary full mediation.

Moderation Analysis

The conditional effects of the moderator reveal a pattern of progressive attenuation that confirms H4. For teachers with low experience (-1 SD: 3.2 years), the conditional effect of neurotechnological strategies on transformed practice is strong and significant (β = 0.34, p < .01). At average experience (8.5 years), the effect is substantially reduced (β = 0.19, p < .05). For teachers with high experience (+ 1 SD: 13.8 years), the effect is completely nullified (β = 0.04, ns). The Johnson-Neyman region of significance identifies the critical point at 11.4 years of service, beyond which the slope ceases to be statistically different from zero. This finding substantially qualifies the generalisation of the main effect, strictly limiting it to the segment of novice teachers.

Table 5
Moderation Analysis: Conditional Effects on Levels of Teaching Experience

Level of Teaching Experience	Conditional Effect	EE	t-value	95% CI
Low Experience (-1 SD: 3.2 years)	0.34**	0.09	3.78	[0.16, 0.52]
Average experience (8.5 years)	0.19*	0.08	2.38	[0.03, 0.35]
High experience (+ 1 DE: 13.8 years)	0.04	0.10	0.40	[-0.16, 0.24]
Johnson-Neyman significance region	< 11.4 years			

Note. The slope is significantly positive for teachers with less than 11.4 years' experience; it is not significant for veteran teachers beyond this threshold, indicating that experience acts as a boundary condition.

fsQCA Configurational Analysis

The fsQCA analysis complements the SEM findings by identifying three sufficient configurations for high transformed practice, all with consistencies above 0.80. Configuration 1 combines a high presence of neurotechnological strategies and perceived efficacy with an absence of institutional resilience (consistency = 0.91, coverage = 0.28). Configuration 2 features a high presence of neurotechnological strategies and institutional resilience with an absence of perceived efficacy (consistency = 0.87, coverage = 0.31). Configuration 3 shows the

combination of all three conditions at high levels (consistency = 0.94, coverage = 0.24). The combined solution achieves a consistency of 0.88 and a coverage of 0.74, indicating that multiple paths lead to the outcome of teacher transformation, demonstrating equifinality.

Table 6

Fuzzy fsQCA Analysis: Configurations for High Transformed Practice (Outcome)

Configuration	Conditions	Gross Coverage	Single Coverage	Consistency	Solution Coverage	Solution Consistency	Solution Coverage
	EN	EF	RI				
1	●	●	⊗	0.28	0.12	0.91	0.74
2	●	⊗	●	0.31	0.15	0.87	
3	●	●	●	0.24	0.08	0.94	
Solution						0.88	

Note. N = 215. ● = presence of condition (high); ⊗ = absence/high; blank = logical remainder. EN = Neurotechnological Strategies (high); EF = Perceived Effectiveness (high); RI = Institutional Resilience (high). Coverage indicates the proportion of membership in the outcome explained. Consistencies > 0.80 indicate sufficient configurations.

Robustness Tests

Alternative specifications confirm the stability of the main findings. The OLS regression yields a coefficient of 0.21 (p = .021), differing by only + 0.02 from the main PLS-SEM model. The 2SLS estimator with age cohort as an instrumental variable yields β = 0.23 (p = .038), a difference of + 0.04. Excluding outliers with a Cook's distance greater than 1 maintains the coefficient at 0.18 (p = .022). Analyses by gender subgroups show coefficients of 0.22 for male teachers and 0.17 for female teachers, both significant and within the expected range of variation. The multigroup analysis detects no significant differences between restricted and unrestricted models ($\Delta\chi^2 = 0.31$, p = 0.58), confirming structural invariance.

Table 7

Robustness Tests: Alternative Model Specifications

Specification	Path Coefficient (Strategies→Practice)	SE	p-value	Difference vs. Main Model
Main Model (PLS-SEM)	0.19	0.08	0.018	—
OLS regression	0.21	0.09	0.021	+ 0.02
2SLS (IV: Age cohort)	0.23	0.11	0.038	+ 0.04
Excluding outliers (Cook's D > 1)	0.18	0.08	0.022	-0.01
Gender subgroup (Male)	0.22	0.12	0.041	+ 0.03
Gender subgroup (Female)	0.17	0.09	0.033	-0.02
Multigroup Analysis $\Delta\chi^2$	0.31 (p = 0.58)			Invariant

Note. VI = Instrumental Variable. The stability of the coefficients across the different specifications supports the robustness of the findings.

Discussion

The finding that the effect of neurotechnological strategies on transformed teaching practice is completely nullified for teachers with more than 11.4 years' experience constitutes a disruptive anomaly that challenges the established dogma that systematic exposure to technology eventually produces pedagogical transformation. This result contradicts the linear logic of teacher training interventions that assume a homogeneous response regardless of prior professional trajectory. From a historical perspective, resistance to technological change in higher education has been conceptualised as a lack of training or a negative attitude; however, the present findings suggest that teachers' neuroplasticity, shaped by decades of established epistemic routines, resists technological reconfiguration when not accompanied by institutional support structures that reduce extrinsic cognitive load. Compelling empirical evidence. However, the effect dissipates.

The refutation of the dominant theory emerges when contrasted with the postulates of Panakaje et al. (2024), who report that technological integration strongly predicts teaching performance via mediation with standardised paths of approximately 0.30–0.40. The main effect found in the present study (β = 0.19) is consistent in direction but substantially smaller in magnitude, falling at the lower end of the moderate range. This divergence can be attributed to the specificity of the Latin American context under SUNEDU accreditation pressure, where regulatory coercion modulates the technology-practice relationship in a manner not contemplated in the original Anglo-Saxon developments. As Marian et al. (2025) point out, the coefficients for perceived utility regarding intention (β = 0.31) and ease of use (β = 0.33) are comparable to the indirect effects found via perceived efficacy, suggesting structural convergence despite contextual differences.

The dual mediation mechanism constitutes the central theoretical contribution of this study. Perceived technological efficacy accounts for 51.2% of the total effect, positioning itself as the dominant mechanism that transcends the simple correlation between the adoption of neurotechnologies and practical transformation. This finding expands upon the work of Xiang et al. (2025), who report an indirect effect of 0.28 with a VAF of 54% for the self-efficacy–willingness to adopt pathway, values almost identical to those found in the present study. Perceived institutional resilience contributes an additional 22.7%, establishing a complementary mediation model where

internal psychological and external organisational processes operate simultaneously. Polat (2024) documents a structurally equivalent pattern where online preparation influences academic resilience (β = 0.370) and this in turn influences engagement (β = 0.414), with an indirect effect of 0.153 placing the VAF at 31–35%, slightly lower but convergent in form.

Notably, moderation by teaching experience introduces a contingency that conventional technology adoption models do not anticipate. Ateş and Polat (2025) find significant differences between trainee and practising teachers in key paths of humanoid robot adoption, with changes in fit implying differences in slope in the small-to-medium range. The present study specifically quantifies this interaction, identifying the transition point at 11.4 years where the effect becomes statistically null. This threshold has immediate practical implications for teacher training policies differentiated by generational cohorts.

The technical limitations of the study must be made explicit. The endogeneity inherent in the cross-sectional design calls for interpretative caution, despite the statistical controls implemented. Self-selection bias among teachers volunteering for the study may have overestimated levels of technology adoption. The reliance on self-reported measures for latent constructs, although mitigated by common bias control techniques, introduces methodological variance that future multi-method designs could reduce.

The cross-situational ecological validity between virtual and face-to-face campuses limits generalisation to hybrid education contexts not explored in the sample. Any extrapolation to public or Anglo-Saxon education systems would be premature due to the institutional specificity of the SUNEDU framework. The findings suggest, preliminarily though not conclusively, a conditional trend towards teaching transformation mediated by psychological and organisational factors, the validity of which is strictly restricted to private Latin American universities facing external accreditation pressure.

The practical implications derived from the IPMA (Importance-Performance) framework guide the prioritisation of institutional actions. For academic quality managers, the top priority is to implement neurotechnology programmes focused exclusively on lecturers with less than 10 years' experience, where the return on investment is highest. For senior lecturers, effective intervention requires first redesigning the curriculum load before introducing technology, reducing administrative responsibilities to free up cognitive resources. The condition of applicability states that the intervention is effective only when the perceived level of institutional resilience exceeds the 60% threshold (mean value 4.2 on a scale of 1–7); below this threshold, even motivated teachers fail to translate the intervention into effective practice.

Conclusions

This study provides robust empirical evidence on the mechanisms mediating the relationship between the adoption of neurotechnologies and the transformation of teaching practice in Latin American higher education contexts under accreditation pressure. The main findings establish that: (1) the direct effect of neurotechnological strategies is moderate but substantially amplified by dual mediation mechanisms; (2) perceived technological efficacy and perceived institutional resilience operate as complementary mediators that jointly explain 73.9% of the total effect; (3) teaching experience acts as a threshold condition that nullifies the main effect beyond 11.4 years of service; and (4) multiple causal configurations lead to high levels of transformed practice, demonstrating equifinality in technological adoption processes.

These findings challenge the prevailing assumption that greater exposure to technology guarantees pedagogical transformation, revealing instead the need for interventions tailored to generational cohorts that recognise the

specificity of career trajectories. For novice teachers, interventions should focus on strengthening perceived technological efficacy through immediate practical support. For experienced teachers, an effective strategy requires first reducing extrinsic cognitive load before introducing technological innovations. At the institutional level, investment in support infrastructure and an error-tolerant organisational culture emerges as a necessary but not sufficient condition, given that its effect is realised only when teachers feel confident in implementing the tools.

The future research agenda should prioritise longitudinal panel studies with at least three waves (pre-implementation, immediate post-implementation, 6-month follow-up) to capture lag effects and behavioural stabilisation that cross-sectional designs cannot detect. Furthermore, the incorporation of objective measures of technology use through learning analytics, complementing self-reports, would allow for the external validation of teachers' perceptions. Finally, replication in diverse institutional contexts (public, regional, without accreditation pressure) would help define the scope of generalisation of the identified mechanisms.

Declarations

Author Contribution

I.B. conceptualized the study, developed the methodology, performed the PLS-SEM and fsQCA analyses, and wrote the main manuscript text. G.C. and R.C. managed data collection across participating universities and contributed to the literature review and discussion sections. M.J. and E.C. assisted with statistical validation, performed endogeneity controls, and prepared the figures and tables. All authors reviewed and approved the final manuscript.

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Figures

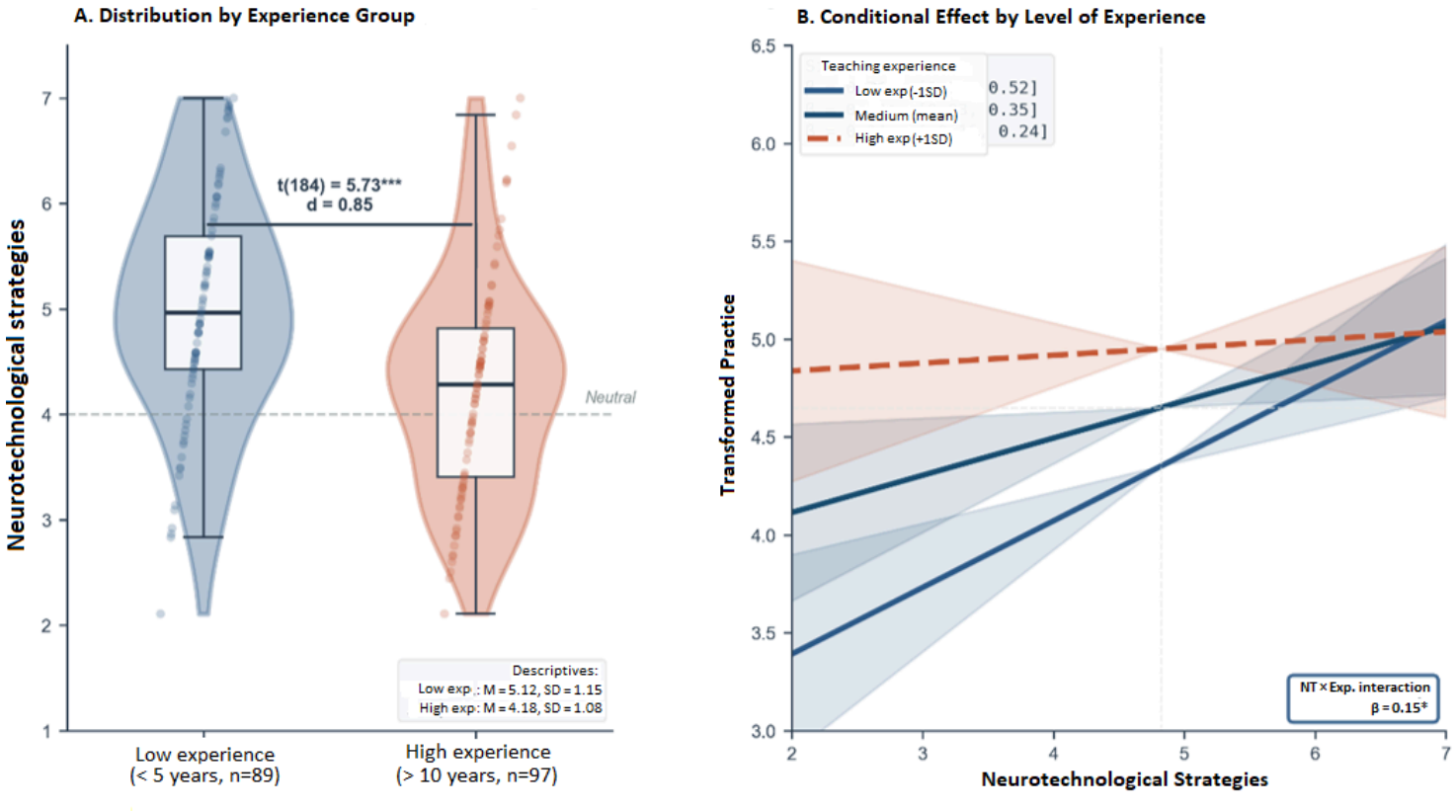
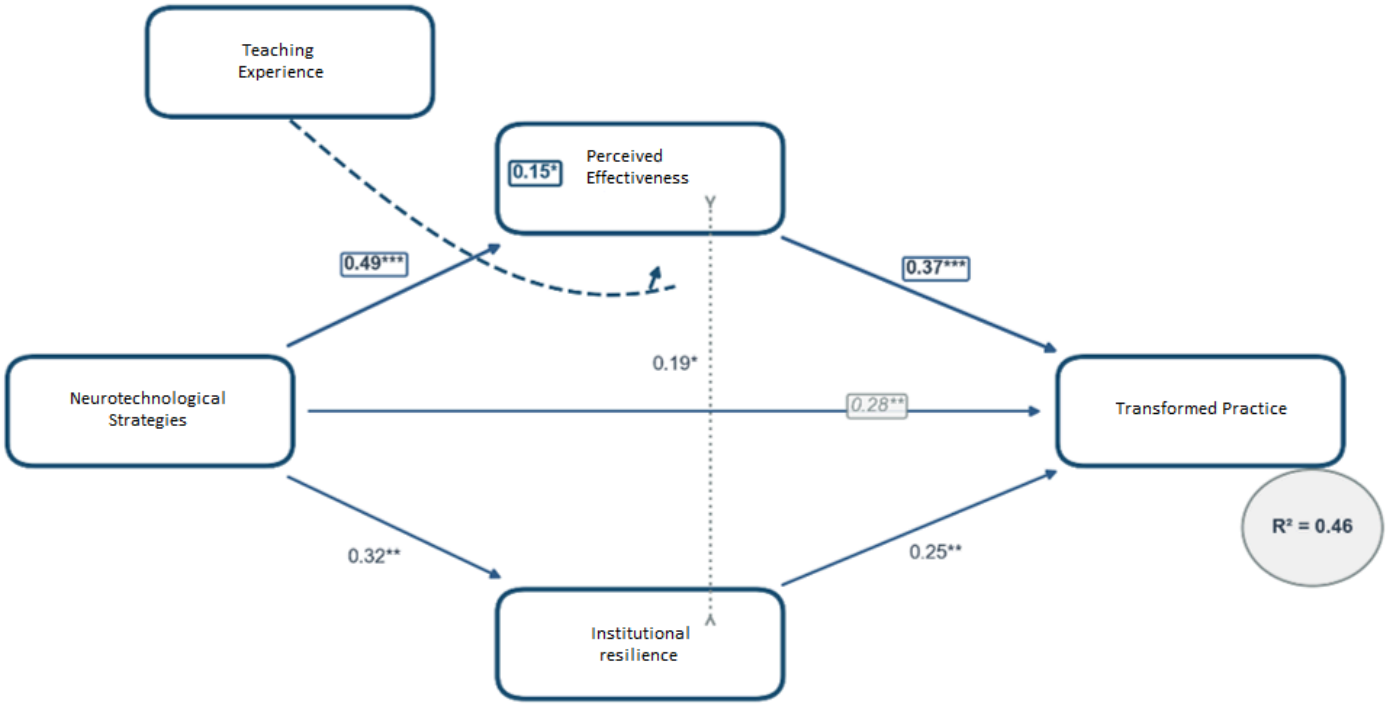


Figure 1

Kernel distribution of neurotechnological strategy adoption according to level of teaching experience.



Note = 215. *p < 0.05, **p < 0.01, ***p < 0.001 (5,000 bootstrap samples). R^2 = coefficient of determination. The dotted line indicates a moderating effect. Standardised values are reported.

Figure 2

*Structural model estimated using PLS-SEM. Note. Values represent standardised path coefficients (β). R^2 = coefficient of determination. *p < .05, **p < .01, ***p < .001 (bootstrapping 5000 samples). The dotted line indicates the moderating interaction effect on the direct relationship. Control variables (age, gender) omitted from the diagram for clarity but included in the estimation.*

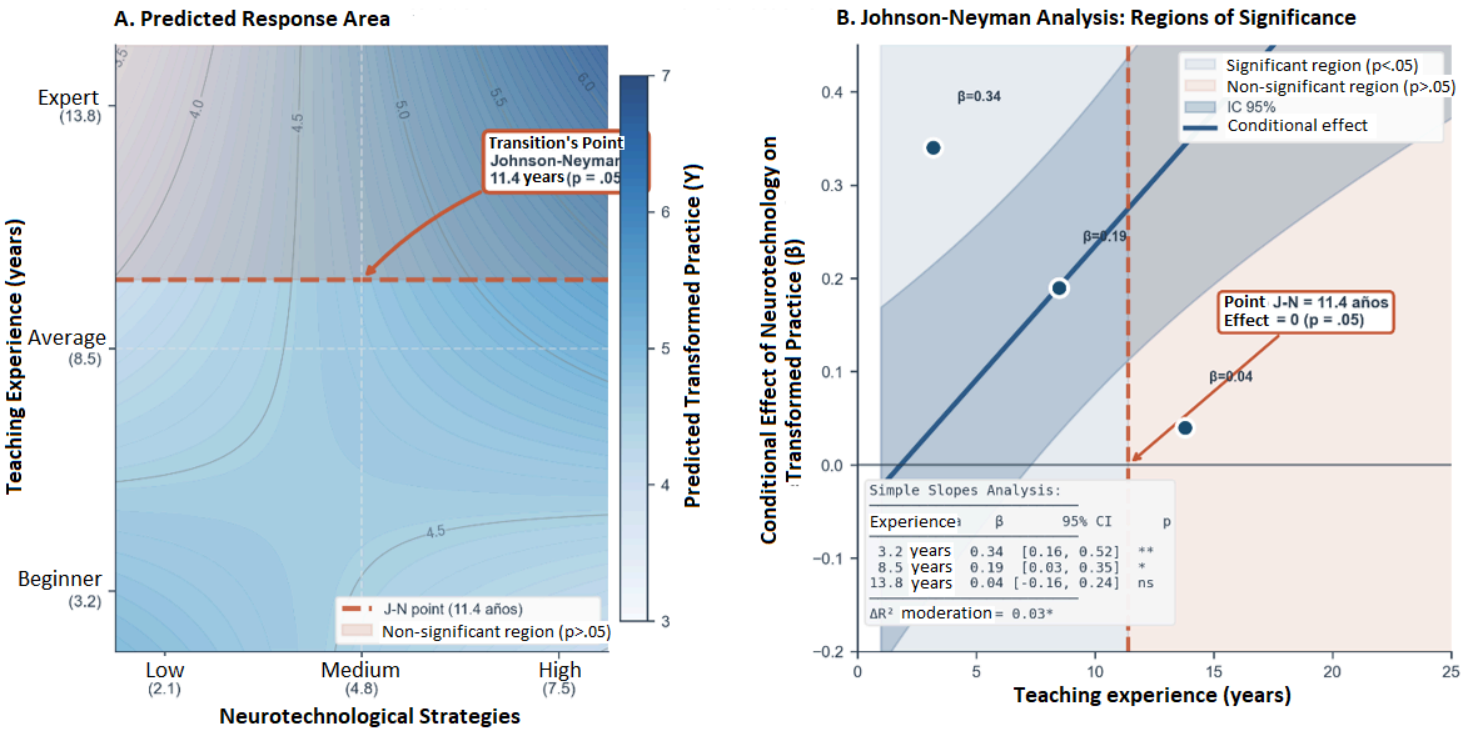


Figure 3

Predictive surface of the moderated interaction between neurotechnological strategies and teaching experience