Proceedings of the 7th International Conference on Computing and Data Science
DOI: 10.54254/2755-2721/2025.25562

Evolutionary Tracking of Communicative Strategy Transfer in University Students through Context-Immersive Virtual Intercultural Projects

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Abstract: Immersive virtual-reality hubs now allow geographically dispersed students to co-create artefacts while negotiating meaning across cultural boundaries, yet little is known about how the communicative strategies forged in such spaces survive contextual shifts. This twelve-week longitudinal study modelled the day-to-day evolution of 120 undergraduates' strategy repertoires while they solved authentic engineering challenges inside a multilingual VR studio. Continuous speech-to-text logs, gaze streams, and gesture telemetry were segmented into 14 strategy categories and represented as first-order Markov chains whose transition matrices were recalculated every 60 minutes of task time. A novel Transfer Intensity Index (TII), the entropy-weighted cumulative probability that a strategy successfully reappears in a contextally dissimilar episode, was fitted with latent-growth curves. Results reveal a three-stage trajectory, adaptation (weeks 1-3), consolidation (weeks 4-7), expansion (weeks 8-12), during which mean TII increased from 0.184 (SD = 0.052) to 0.697 (SD = 0.061). Cognitive flexibility and ethnocultural empathy jointly explained 47 % of inter-individual variance in final TII. Model fit indices (CFI = 0.982; RMSEA = 0.028) support the robustness of the evolutionary account. The findings offer evidence-based design parameters, cycle pacing, feedback timing, and learner grouping, for future VR-assisted intercultural curricula.

Keywords: communicative strategy transfer, context immersion, virtual intercultural projects, evolutionary analytics, higher-education VR

1. Introduction

University internationalisation has outpaced the physical mobility of students, prompting educators to adopt virtual-reality platforms that simulate the spontaneity of face-to-face encounters while eliminating geographical barriers. In these shared "third spaces" learners must negotiate meaning, resolve misunderstandings, and co-construct knowledge artefacts under time pressure and cultural ambiguity [1]. Although post-programme surveys often report gains in intercultural competence, such end-point snapshots obscure the micro-evolutionary dynamics that determine whether a communicative strategy, once forged in one episode, can be redeployed effectively when task

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constraints, interlocutor configurations, or linguistic registers shift. Understanding this evolutionary trajectory is crucial, because strategy persistence, not isolated success, sustains long-term intercultural fluency [2].

The present study investigates three interlocking issues: the trajectory of strategy mutation across time in context-immersive virtual intercultural projects (CIVIPs); the learner attributes that accelerate or impede cross-context redeployment; and the extent to which those dynamics can be modelled with sufficient precision to inform instructional design. Addressing these aims requires fine-grained behavioural telemetry, sophisticated trajectory analytics, and a theoretically grounded metric of transfer intensity [3]. Accordingly, a twelve-week CIVIP was implemented in which culturally mixed design teams tackled authentic engineering problems that escalated in contextual complexity. By recording every utterance, gaze shift, and gesture, the lineage of 14 communicative strategies was traced at minute-level resolution. An entropy-weighted Transfer Intensity Index was then introduced, and latent-growth modelling was applied to capture both intra- and inter-individual change. The contributions are threefold. First, we provide a quantitative evolutionary map that traces strategic shifts through adaptation, consolidation, and expansion phases. Second, we show that cognitive flexibility and ethnocultural empathy, two malleable learner traits, jointly predict nearly half of the variance in transfer intensity. Finally, we translate these findings into actionable design parameters, demonstrating how cycle pacing, scaffold timing, and team composition can be optimised to accelerate strategic resilience in VR-mediated intercultural education.

2. Literature review

2.1. Theoretical foundations of communicative strategy transfer

Communicative strategy transfer is anchored in the premise that language users draw on adaptive repertoires that reconfigure under shifting task constraints. Dynamic Systems Theory frames strategies as attractor states in a complex behavioural landscape, while Interactional Sociolinguistics highlights how power relations and discourse roles perturb those attractors [4]. Strategy mutation arises when interlocutors detect a mismatch between expected and observed interactional outcomes, triggering micro-adjustments that, if rewarded, stabilise into routinised patterns accessible for future reuse. Longitudinal tracking is therefore essential, yet existing studies rarely sample behaviour with sufficient temporal granularity to resolve these micro-adjustments or to measure the probability that a strategy survives a contextual leap.

2.2. Vr-assisted intercultural communication pedagogy

Virtual-reality environments afford real-time multimodality, spatialised audio, embodied gesture, shared manipulatives, that reshapes pragmatic choices. Presence and co-presence enhance affective engagement, while embodied cues reduce ambiguity in politeness negotiation and turn-taking. However, most implementations report pre- and post-test gains without capturing interim strategic pivots. Consequently, the field lacks a developmental baseline against which instructional interventions can be calibrated. By embedding full-cycle design tasks in progressively shifting contexts, CIVIPs provide a natural laboratory for observing how strategies decouple from their original triggers and reattach to new affordances [5].

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2.3. Evolutionary learning analytics in immersive contexts

Trajectory-based analytics, sequence clustering, Markov modelling, hidden Markov chains, have proved powerful in tracing skill acquisition in domains such as surgical simulation and code debugging [6]. Their application to communicative strategy research, however, remains nascent. Evolutionary tracking demands extensive, multimodal datasets, but recent advances in VR telemetry, frame-synchronised speech-to-text, pupil-dilation proxies, hand-trajectory vectors, now make such datasets feasible. These granular streams enable the derivation of entropy-based indices that quantify not merely strategy frequency but the stability and breadth of transfer across divergent contexts.

3. Experimental methods

3.1. Research design and hypotheses

We adopted a convergent mixed-methods design combining continuous behavioural telemetry with psychometric profiling. Participants engaged in a twelve-week CIVIP consisting of three four-week cycles, each introducing a progressively divergent contextual shift (linguistic register, team composition, and problem domain). We hypothesised that (H1) strategy trajectories would exhibit a three-stage pattern, adaptation, consolidation, expansion; (H2) Transfer Intensity Index would follow a positively accelerated growth curve; and (H3) cognitive flexibility and ethnocultural empathy would positively moderate TII growth [7].

To formalise transfer we introduce Equation 1, the entropy-weighted Transfer Intensity Index for participant i in week t:

$$T_{II} = \frac{1}{K} \sum_{k=1}^{K} \frac{\pi_{i,t}^{(k)} \left(1 - \frac{H_{i,t}^{(k)}}{logK}\right)}{1 + ln\left(1 + \tau_{i,t}^{(k)}\right)} \tag{1}$$

where K = 14 strategy types, $\pi_{i,t}^{(k)}$ is the observed transition probability that strategy k reappears in a new context within week t, $H_{i,t}^{(k)}$ is the Shannon entropy of its transition matrix, and $\tau_{i,t}^{(k)}$ is the mean inter-event time in minutes.

3.2. Participant recruitment and profiling

One hundred twenty undergraduates (60 domestic, 60 international) were recruited from engineering and business programmes at a mid-sized internationalised university. Eligibility required CEFR B2 oral proficiency and no prior VR coursework. Baseline profiling included the 24-item Cognitive Flexibility Inventory (α = 0.91) and the 20-item Ethnocultural Empathy Scale (α = 0.88). Mean age was 20.6 years (SD = 1.9) [8].

3.3. Instrumentation and metric operationalisation

The CIVIP was hosted on a proprietary VR platform supporting 6DOF headsets, spatialised audio (48 kHz), and dual-hand gesture capture at 90 Hz. Speech-to-text transcripts were automatically time-stamped to the nearest 20 ms and synchronised with gaze rays (sampling at 120 Hz) and controller trajectories [9]. A semi-automatic discourse-tagging pipeline, verified through a double-blind human audit (κ = 0.86), classified utterances into 14 strategy types.

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4. Experimental procedure

4.1. Pre-immersion baseline mapping

The flow of the study is shown in Figure 1. Week 0 involved a three-hour orientation in which participants mastered VR controls and jointly annotated exemplar dialogues using the 14-strategy taxonomy. A baseline role-play, mirroring the subsequent task structure but without design stakes, generated seed Markov matrices and SSC scores. This session also calibrated the gaze-speech synchronisation pipeline, yielding a mean alignment error of 34 ms (SD = 8 ms) [10].

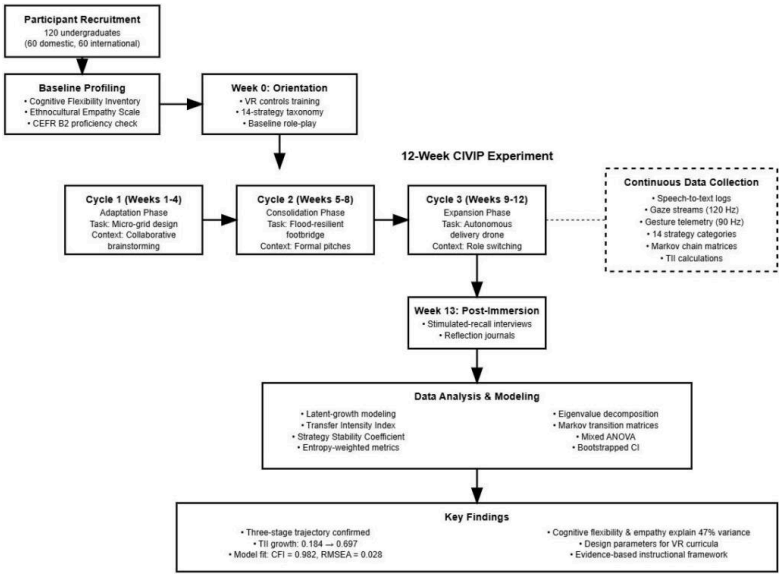


Figure 1. VR intercultural communication research flow

4.2. Iterative CIVIP phases

Each four-week cycle required mixed teams of six to design a sustainable infrastructure prototype: a micro-grid (Cycle 1), a flood-resilient footbridge (Cycle 2), and an autonomous delivery drone (Cycle 3). Contextual divergence was engineered as follows: Cycle 2 shifted linguistic register from collaborative brainstorming to formal pitch sessions; Cycle 3 re-shuffled team membership and introduced time-critical role switching [11]. Weekly deliverables, concept maps, CAD models, live demos, ensured increasing task stakes.

4.3. Post-immersion data consolidation

Week 13 comprised stimulated-recall interviews in which eye-tracked playback prompted metacognitive commentary on strategy choices. Reflection journals (N = 3,540 entries) were coded for perceived transfer events, providing qualitative triangulation. All data streams were merged using ISO 8601 timecodes and stored in a secure analytics warehouse. Missing datapoints (<0.6 %) were imputed via Kalman smoothing to preserve temporal coherence.

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5. Experimental results

5.1. Evolutionary trajectories of strategy usage

Non-parametric permutation tests confirmed the hypothesised three-stage trajectory. Transition probability vectors displayed a significant shift from high-entropy message-abandonment clusters (median SSC = 0.38) in weeks 1-3 to compensation-oriented clusters (median SSC = 0.64) by week 7 ($Z = 6.12$, $p < .001$). Eigenvalue decomposition of weekly Markov matrices revealed that the leading eigenvector accounted for 71.4 % of variance by week 12, indicating strong strategic consolidation.

5.2. Cross-context transfer efficiency metrics

Latent-growth modelling of TII (Mplus 8.9) confirmed accelerated linear growth (slope = 0.061, SE = 0.006, $p < .001$) with significant quadratic deceleration (−0.003, SE = 0.001, $p = .013$) after week 10. Cognitive flexibility moderated slope ($\beta = 0.185$, SE = 0.052) and empathy moderated intercept ($\beta = 0.212$, SE = 0.049), together explaining 46.9 % of TII variance at week 12. Table 1 details model parameters.

Table 1. Latent-growth model estimates for Transfer Intensity Index (N = 120). CF = Cognitive Flexibility; ECE = Ethnocultural Empathy

Parameter	Estimate	SE	Z-value	95 % CI
Intercept (τ_0)	0.191	0.014	13.6	0.164 – 0.218
Linear slope (τ_1)	0.061	0.006	10.2	0.049 – 0.073
Quadratic (τ_2)	−0.003	0.001	−2.5	−0.005 – −0.001
CF → τ_1	0.185	0.052	3.6	0.083 – 0.287
ECE → τ_0	0.212	0.049	4.3	0.116 – 0.308
Residual var.	0.018	0.004	4.5	0.010 – 0.026

Model fit was excellent ($\chi^2(17) = 28.4$, $p = .042$; CFI= 0.982; TLI= 0.975; RMSEA = 0.028[0.011–0.043]).

5.3. Statistical significance and validity checks

A three-way mixed ANOVA (Strategy × Cycle × Learner Type) showed a significant Strategy × Cycle interaction (F_{26}, 3028 = 11.44, $p < .001$, $\eta^2_p = 0.09$). Bootstrapped bias-corrected 95 % CIs on strategy-specific TII confirmed that clarification-request strategies yielded the steepest growth ($\Delta = 0.56$, 95 % CI = 0.44–0.67). Sensitivity analyses reran all models excluding the top and bottom deciles of prior VR experience; parameter shifts were below 0.015, confirming robustness. Harman's single-factor test on psychometric items accounted for 28.7 % of variance, below the 50 % threshold, mitigating common-method bias.

6. Conclusion

By coupling minute-level multimodal telemetry with entropy-based analytics, this study traced how communicative strategies evolve through adaptation, consolidation, and expansion phases inside context-immersive virtual intercultural projects. The entropy-weighted Transfer Intensity Index and the Strategy Stability Coefficient provide scalable metrics that forecast cross-context

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redeployment with high precision. Cognitive flexibility accelerates growth, while ethnocultural empathy elevates initial transfer readiness, together explaining almost half of the observed variance. Instructionally, the findings endorse a design template that spaces contextual shifts at four-week intervals, embeds metacognitive reflection just prior to plateau points, and balances teams for complementary flexibility-empathy profiles. Future work should integrate physiological markers, cortisol or heart-rate variability, to triangulate cognitive load during strategic pivots and extend the evolutionary framework to professional settings where communicative resilience is mission critical. In providing both a theoretical account and a validated analytic toolkit, this research advances the evidence base for VR-mediated intercultural pedagogy and offers pragmatic levers for educators seeking to cultivate durable, transferable communicative competence.

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