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NEUROBIOLOGICAL INSIGHTS INTO THE FACULTY OF LANGUAGE WITHIN BIOLINGUISTICS

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Abstract: In the field of biolinguistics, theoretical models treating language as a biological system have advanced rapidly, yet the neurobiological evidence underpinning these models has lagged behind, creating a significant gap between theory and data. This study bridges the theoretical framework of biolinguistics with empirical neurobiological evidence to examine the neural foundations of the faculty of language, both in its broad (FLB) and narrow (FLN) senses. Drawing on recent neurobiological findings, the study demonstrates that the modular architecture of FLB—comprising phonological-phonetic, syntactic, semantic, and pragmatic modules—is instantiated in distinct yet dynamically interacting neural circuits. Notably, the left inferior frontal gyrus (IFG) and the posterior superior temporal gyrus (pSTG) play central roles in syntactic computation, while the left superior and middle temporal gyri are primarily involved in semantic computation. Evidence from comprehension studies further highlights that syntactic computations may continue beyond the point of initial phrase construction, indicating that syntactic computations are not necessarily complete once their outputs are transmitted to other modules (semantic, pragmatic, phonological-phonetic modules). Regarding FLN, the core syntactic operation merge is shown to be implemented in the BA 44 of the left IFG as the neural locus of external merge. While some cross-species studies suggest merge-like abilities in non-humans, the neurobiological specificity of merge remains uniquely human. Internal merge, responsible for syntactic movement, has not yet been systematically investigated in terms of its neural underpinnings; however, a review of neuroimaging studies involving syntactic displacement suggests that internal merge engages overlapping regions in the IFG, indicating a shared but functionally distinct neural basis. This study affirms the biological grounding of the faculty of language and argues for a more integrative empirical agenda in biolinguistics—one that combines theoretical precision with neuroscientific rigor to uncover the architecture of language.
Keywords: Biolinguistics; Neurobiology of language; The faculty of language; Modularity

1 INTRODUCTION

Biolinguistics highlights the commitment of the generative enterprise to the biological foundations of language, and emphasizes the necessarily interdisciplinary character of such enterprise [1]. It emerged in the late 1950s from early collaborations between linguists and biologists (Chomsky, Lenneberg, and Salvador Luria), and was formally established as a scientific framework with Lenneberg's seminal work *Biological Foundations of Language* [2-3], which laid the groundwork for subsequent theoretical and empirical developments. As a research program, Biolinguistics addresses five fundamental issues in the field: what the knowledge of language is; how that knowledge develops in individuals; how it is used; how it is represented in the brain; and how it evolved in our species [4]. In answering the first three questions, scholars in the field typically conceive knowledge as a specific neurophysiological state of the brain: genetically specified and shaped by environmental input through neurodevelopmental processes, culminating in a mature language organ that enables thought, speech, and comprehension. By contrast, the latter two questions—neural representations and evolutionary origin—cannot be resolved solely through abstract theorizing or behavioral observation; they demand interdisciplinary neurobiological investigations and diachronic, cross-species research. Indeed, the generative tradition has often remained at a highly abstract level, rendering concrete biological inquiry challenging [5]. To move beyond this abstraction and fully articulate the biological foundations of language, rigorous neurobiological inquiry is both necessary and long overdue.

Central to biolinguistics is to identify the property of the faculty of language, which Hauser, Chomsky, Fitch divided into the faculty of language in the broad sense (FLB) and the faculty of language in the narrow sense (FLN) [6]. FLB encompasses the sensory–motor system (the phonological–phonetic module) responsible for externalization and the conceptual–intentional system (the semantic and pragmatic modules) responsible for thought and action planning [7], and the computational capacity for recursive merge—FLN [i.e., syntactic module (including lexicon)]—which alone underlies our uniquely human ability to generate an infinite array of expressions from a finite set of elements. In this framework, language is generated by first retrieving lexical items from the lexicon and then assembling them into hierarchical structures through syntactic computation. These candidates (i.e., syntactic representations) are subsequently mapped onto the phonological-phonetic module for auditory processing, and onto the semantic and pragmatic modules for interpretation. Moreover, these modules do not operate in isolation; rather, they interact dynamically, allowing for continuous exchange and integration of information across various modules of the faculty of language. To illustrate this, before we utter "the river runs," we extract the (syntactic, semantic, phonological, and phonetic) representations of "the", "river" and "runs," generate and evaluate possible syntactic representations (e.g., *"river runs the," *"the runs

river," "the river runs"), and only those that satisfy the interfaces between syntactic module and other modules (e.g., semantic, phonological-phonetic modules) are ultimately phonologically realized and interpreted as "the river runs".

This naturally leads us to ask: what neurobiological evidence currently supports such an architecture of the faculty of language? Or is this framework still largely confined to the realm of theoretical speculation? To date, much of biolinguistic research has remained predominantly theoretical, relying on inductive and deductive reasoning to formulate hypotheses [8], which are subsequently tested through behavioral experiments. In contrast, empirical evidence from neuroimaging studies remains relatively limited—particularly within biolinguistics, a field historically grounded in theoretical innovation, despite the originality and far-reaching implications of its proposals. Against this backdrop, the present study aims to help bridge the gap between biolinguistic theory and empirical inquiry by systematically evaluating the neurobiological substrates of the faculty of language—both in its broad (FLB) and narrow (FLN) senses—through a critical and integrative synthesis of existing neural evidence.

2 NEURAL FOUNDATIONS OF THE FACULTY OF LANGUAGE IN THE BROAD SENSE

The neural underpinnings of the FLB reside in the precisely coordinated activity of distinct cortical and subcortical regions in our brain, as well as in the dynamic exchange of information among these regions, often via functional connectivity or long-range white matter tracts. Biolinguistics, by conceptualizing language as a biological organ, tends to assume that these neural systems correspond to theoretically motivated modules—phonological-phonetic, syntactic, semantic, and pragmatic modules—each of which is instantiated in specific, functionally or anatomically specialized, and reproducible neural circuits that can be studied across individuals and populations.

To date, the majority of empirical support for this modular architecture of FLB has come from neurobiological investigations from Friederici and colleagues [9-10]. They have provided perhaps the most comprehensive neuroanatomical model of language comprehension, delineating successive yet interactive processing stages. In their framework, an initial acoustic–phonological analysis is reflected by the N100 component (occurring around 100 ms post-stimulus) and arises in primary auditory cortex. From there, signals bifurcate: a posterior pathway toward the planum temporale and posterior superior temporal gyrus (pSTG) specializes in segmental, phonemic detail, while an anterior route toward the planum polare and anterior superior temporal gyrus (aSTG) processes prosodic, suprasegmental cues. Crucially, these pathways operate in parallel and engage both hemispheres, with the left hemisphere preferentially supporting fine-grained, time-sensitive analyses and the right hemisphere more sensitive to contour and rhythmic structure. Within the left hemisphere, processed auditory representations are further parsed into three interleaved stages. First, ventral Brodmann area 44 (BA 44) in the inferior frontal cortex instantiates rapid, automatic initial phrase-structure building—indexed by the ELAN (early left-anterior negativity) between 120 and 250 ms. This stage aligns neatly with the biolinguistic notion of a syntactic module in FLB that generates hierarchical structure from lexical items. Second, between 300 and 500 ms, the LAN and N400 components reflect parallel semantic and thematic integration processes, recruiting left superior and middle temporal gyri along with BA 45/47 in the inferior frontal cortex. These activations correspond to the semantic module of FLB, demonstrating how meaning is computed in real time. Third, syntactic relations that involve long-distance dependencies—such as in center-embedded or subordinate clauses—further re-engage BA 44 and pSTG, illustrating the sustained role of the syntactic module in handling complex structures. Finally, the P600 component (approximately 600 ms) indexes the integration of syntactic and semantic representations in the posterior superior temporal sulcus (pSTS) and adjacent pSTG, indicating the convergence of multiple pathways into a unified interpretation. Right-hemisphere mechanisms complement these left-lateralized processes by parsing prosodic phrase boundaries. Specifically, right superior temporal and inferior frontal regions are engaged in prosodic processing, with interhemispheric coordination mediated by the corpus callosum. This bilateral division of labor underscores FLB's design that the sensory–motor and conceptual–intentional systems operate in concert, yet with specialized subcomponents tuned to distinct informational streams. Taken together, this neuroanatomical evidence offers compelling support for the modular and interactive nature of FLB, bridging abstract theoretical constructs with temporally and spatially specific brain mechanisms.

Although these findings illustrate a modular decomposition of language comprehension processes, it is important to emphasize that neural evidence also indicates a high degree of parallel processing among the modules of FLB. Contrary to a strictly linear biolinguistic pipeline—in which lexical retrieval feeds into syntactic assembly, which then sequentially sends outputs to the semantic, pragmatic, and phonological–phonetic modules—time-resolved neural recordings reveal that outputs from early phrase-structure building rapidly cascade into semantic networks, even as syntactic computations, such as the processing of long-distance dependencies, continue to unfold. This dynamic temporal profile suggests that multiple components of the language system may partially operate in parallel rather than being activated in a strictly sequential manner. Moreover, the evidence strongly indicates that these modules are densely interconnected—for instance, through the flow of information between syntactic and semantic processors in the left hemisphere, and through the integration of phonological processing via white matter tracts connecting to the right hemisphere. Such a highly interactive and temporally flexible architecture aligns closely with the central claim of biolinguistics: that the modules jointly constitute a human language system (FLB) that is both flexible and biologically constrained.

It is also important to realize that biolinguistic models maintain a fundamental interdependence between language comprehension and production (i.e., generation), positing that both domains rely on shared core computational mechanisms that collectively support linguistic competence. Demonstrating converging evidence across these domains

is therefore crucial not only to substantiate the integrative architecture of the FLB, but also to establish a robust neurobiological foundation for biolinguistic theory. To fully validate the design principles underlying FLB, empirical inquiry must extend beyond aforementioned comprehension to include language production paradigms, which remain comparatively underexplored in the existing literature [11-13]. Three principal methodologies offer complementary insights into the neural bases of production. First, lesion studies involving aphasic patients—particularly those with focal damage to Broca's or Wernicke's areas—have shown that impairments in the production of phonological, syntactic, or semantic components can be selectively traced to specific cortical regions. Although interindividual variability present methodological challenges [14], the recurrence of similar deficits across patients provides compelling support for modular specialization. Second, elicitation of speech errors in neurologically intact individuals—through techniques such as tongue twisters or speeded naming tasks—can reveal breakdowns in specific processing stages, illustrating, for instance, that phonological encoding errors may occur independently of semantic selection. Third, experimental paradigms that prompt target utterances via picture naming, word fluency tasks, or scripted dialogues allow researchers to systematically investigate production subroutines under controlled conditions. While such tasks often involve some engagement of comprehension circuits (e.g., reading prompts), careful task design in combination with neuroimaging techniques enables researchers to isolate neural activity specific to production processes. By integrating evidence from lesion studies, behavioral experiments, and neuroimaging research, we may map the neural representations for language production—evidence that may offer a more decisive evaluation of the biological foundations of FLB within the biolinguistic framework.

Moreover, the pragmatic dimension of language—often marginalized in comprehension-focused research—is rarely treated as a core component in Friederici's model. Yet this aspect of language use may constitute a fundamental part of the FLB. Mao compellingly argues for the inclusion of a dedicated pragmatic module within the FLB architecture [15]. Drawing on evidence from autism spectrum disorders, he demonstrates that individuals with impaired pragmatic inference do not rely on mind-reading when processing linguistic and communicative demands; instead, they resort to self-sufficient mental computations among organism-internal submodules (e.g., semantic, syntactic modules) or rely on nearly intact grammatical systems. This suggests that there is a strong theoretical rationale for incorporating a pragmatic module into the FLB. In addition, neuroimaging studies of pragmatic inference have implicated bilateral inferior frontal gyri and middle temporal gyri [16], regions that overlap with core semantic networks. This anatomical overlap indicates that pragmatic computation may be closely integrated with semantic computation, rather than residing at the periphery. Incorporating pragmatics into the neurobiological study of core linguistic capacities would not only extend the explanatory power of the FLB but also align with biolinguistics' broader aim of accounting for the full range of human linguistic capabilities.

In summary, current neurobiological evidence on language comprehension largely supports the architecture of the FLB as proposed within the biolinguistic framework, particularly in demonstrating the neural substrates of syntactic and semantic computations and the interactive flow of information among modules. However, complementary findings suggest that syntactic computations may continue beyond the point of initial phrase construction indicating that such operations are not necessarily complete once their outputs are transmitted to other modules. These observations may contribute to refining and extending the FLB model. Moreover, the inclusion of a pragmatic module within the FLB architecture appears theoretically justified, and future neurobiological research on language could further substantiate the validity of this modularization.

3 NEURAL FOUNDATIONS OF THE FACULTY OF LANGUAGE IN THE NARROW SENSE

The concept of merge, introduced by Noam Chomsky, constitutes the core syntactic operation common to all human languages, reflecting a universal property of human cognition. Defined as an unbounded binary set-formation operation, merge applies recursively to generate hierarchical structures. In the case of external merge, two syntactic objects, α and β, are combined to form a new set $\{\alpha, \beta\}$. For instance, merging the lexical items *the* and *river* yields {*the*, *river*}; further merging with a third item, such as *runs*, results in the structure {{*the*, *river*}, *runs*}. Note that the syntactic objects generated by external merge are unordered and must be interpreted by the conceptual-intentional system and externalized by the sensory-motor system.

Beyond external merge, the operation of merge also includes internal merge, which accounts for displacement phenomena observed in natural language. For instance, suppose we begin with the representations such as *Mary is seeing who*, constructed via external merge. To form a *wh*-question like *tell me who Mary is seeing* ~~*who*~~, the *wh*-phrase *who* must move to the edge of the clause via internal merge, yielding a derived structure where the fronted *who* indicates interrogative force, while the unpronounced lower copy *who* retains semantic content for interpretation. This derivational process highlights the core property of internal merge: it repositions existing elements within a syntactic structure rather than introducing new ones, allowing for complex hierarchical configurations to emerge through minimal operations. Notably, this movement-driven operation underlies a wide range of syntactic phenomena across languages—such as question formation, topicalization, and relativization—further illustrating its central role in the generative system.

Crucially, both external and internal merge constitute the core of the FLN—a capacity widely considered unique to humans and central to our species' linguistic competence. It is hypothesized that this capacity emerged in modern humans who first appeared in southern Africa around 200,000 years ago, but before the last major migration out of Africa approximately 60,000 (or possibly 80,000) years ago [17]. This period likely marks a species-specific biological

mutation that endowed humans—with no comparable capacity observed in other primates such as gorillas—with this uniquely human linguistic computation. In what follows, we examine the neural basis of this fundamental property of language, focusing on how recent advances in neuroimaging and comparative research contribute to our understanding of merge as a biologically grounded and potentially uniquely human computational operation.

Neuroscientific evidence bolsters the claim that external merge is a universal human attribute by identifying its biological basis in the brain. Most of this evidence derives from studies of both complex sentence structures and two-word compositions. For the former, Goucha & Friederici employed a multi-level syntax–semantics dissociation paradigm to reveal that the BA 44/45 network in Broca's area operates in concert during full sentence processing [18]; as semantic and derivational morphological cues are incrementally stripped away—leaving only pure syntactic markers—posterior BA 44 alone emerges as the neural "engine" of external-merge operations. This fine-grained functional segregation provides direct and robust support for external merge as a core computational mechanism. Complementing these findings, one MEG study demonstrates that cortical ensembles track hierarchical linguistic units at distinct temporal rates—4 Hz for words, 2 Hz for phrases, and 1 Hz for sentences—across typologically diverse languages, reflecting a merge-driven computation of structure independent of language-specific content [19].

Because complex sentences inherently introduce confounds—such as propositional meaning, increased processing demands, and contextual effects [20]—investigators have turned to the paradigm of two-word phrases to isolate pure syntactic composition. In this domain, Zaccarella & Friederici found that the ventral-anterior subcluster (C3) of left BA 44 exhibits significantly greater activation for externally merged two-word phrases than for unstructured word lists [21], and Schell et al. showed that determiner–noun pairs, which engage basic syntactic computation merge [22], selectively recruit inferior-ventral BA 44 along with the frontal operculum and anterior insula, underscoring BA 44's sensitivity to function-word–driven combinatory operations. An ALE (activation likelihood estimation) meta-analysis also confirmed that merge [23]—the core syntactic mechanism combining words into hierarchies—consistently engages the left BA44 and the posterior STG/STS. BA44 was identified as a pure syntactic processor, while posterior STG/STS integrates syntactic and semantic information. Together, these data define the neural mechanism of external merge as a hierarchical computation powered by BA 44 within a fronto-temporal network specialized for syntactic composition, firmly grounding this mechanism as a universal attribute of human language.

However, behavioral evidence from both human and animal studies might be against the notion that external merge is a uniquely human attribute with a specific biological basis. Research involving monkeys, children, U.S. adults, and native Amazonians demonstrates that recursive sequence generation [24], a fundamental component of merge, is not exclusive to humans and can be observed across different species and cultures, suggesting a broader cognitive capacity rather than a human-specific trait. Furthermore, research on songbirds reveal their ability to learn recursive syntactic patterns [25], indicating that the cognitive mechanisms supporting merge-like processes are present in non-human species as well. While these findings imply a broader cognitive substrate, they do not directly challenge the neurobiological specificity of external merge in humans. To mount a decisive critique, comparable neuroscientific investigations—ideally employing fMRI, MEG, EEG, or invasive recordings—in species such as non-human primates and songbirds are needed to determine whether analogous fronto-temporal circuits underlie their merge-like abilities, and how these circuits diverge from the human blueprint.

Although previous studies have provided neural evidence for the operation of external merge, no research to date has clearly distinguished the neural correlates of internal merge versus external merge. Theoretically, internal merge involves movement of elements within a structure—such as the fronting of a *wh*-word in interrogatives—while external merge introduces new elements into the structure, as in the initial combination of lexical items (see earlier discussions of external merge). Most existing neuroimaging studies have treated the two as functionally equivalent or have overlooked internal merge altogether, with no direct neural comparisons available to dissociate their activation patterns. Nevertheless, we may attempt to infer the neural basis of internal merge by examining well-attested syntactic phenomena that are canonically analyzed as involving this operation. These can include *wh*-movement (e.g., *What did you buy?*, where the *wh*-word is fronted from its base position [26-28]), topicalization (e.g., *This book, I really like.*, with fronting for emphasis; cf. Maki et al. [29]), passivization (e.g., *This book was read by John.*, involving NP movement; cf. Collins [30]), and scrambling (e.g., in Japanese *Sono hon-o Taroo-ga yonda* 'That book, Taro read', where the object precedes the subject without topicalization or focus marking ; cf. Miyagawa [31]). Identifying common activation patterns across these constructions may shed light on the neural substrates of internal merge.

Findings from several neuroimaging studies may support this approach. Ben-Shachar et al. found that syntactic movement [32]—examined through Hebrew topicalization and *wh*-questions—consistently activated the left IFG, left ventral precentral sulcus (vPCS), and bilateral posterior STS, regions that were selectively sensitive to movement-based syntactic contrasts. This supports a stable neural signature for syntactic movement consistent with internal merge. Ohta et al. further demonstrated that scrambling [33], which involves structure-internal displacement, elicited significant activation in the left IFG and lateral premotor cortex—both associated with core syntactic computation—using stimuli from Kaqchikel Maya, a language with flexible word order. Crucially, when controlling for semantic and phonological confounds such as topicalization, the scrambling effect persisted. Similarly, Mack et al. showed that passive sentences [34], which involve NP-movement, triggered stronger activation in the left IFG, as well as bilateral IFG and the left temporo-occipital cortex, compared to active counterparts. The authors interpreted the left IFG activation as reflecting the processing of syntactic displacement, again consistent with the computational role of internal merge. In sum, these studies may converge on the left IFG as key neural substrates for the implementation of internal merge in natural language.

An important consideration is that although existing evidence points to the left IFG as supporting the neural basis of internal merge, it is crucial to recognize that sentence types involving syntactic movement often entail semantic changes as well. For example, *wh*-movement contributes to interrogative force, while topicalization shifts a constituent to the left periphery to mark it as a topic—both operations associated with the CP layer. These constructions are not purely syntactic but carry discourse-pragmatic or interpretive functions that may confound attempts to isolate movement-related activation. While semantic interpretation typically involves left posterior temporal regions, it also engages the left frontal cortex, especially the IFG. This overlap raises the possibility that observed IFG activity reflects a confluence of syntactic computation and semantic integration. Therefore, future efforts to isolate the neural correlates of internal merge must carefully control for semantic factors—ideally by using syntactic contrasts that hold semantic content constant—in order to determine the specific contribution of syntactic movement. Carefully designed paradigms, possibly incorporating artificial grammar learning or minimalist pairwise contrasts, will be essential to teasing apart these intertwined processes and clarifying the precise role of internal merge in our brain. Further, although the left IFG may be the primary candidate region responsible for internal merge, its subregions—such as pars opercularis (BA 44), pars triangularis (BA 55), and pars orbitalis (BA 47)—are likely to support distinct and functionally specialized aspects of linguitistic computation [35]. This implies that internal merge may not be uniformly distributed across the IFG, but rather localized to specific subcomponents depending on the syntactic operation involved. Consequently, future research will need to investigate the left IFG with greater anatomical and functional precision, employing high-resolution neuroimaging and fine-grained task designs to disentangle these subregional contributions.

In sum, merge—the core syntactic operation of the FLN—has garnered growing neuroscientific support as a biologically grounded mechanism. External merge, which combines discrete syntactic objects, is consistently associated with a fronto-temporal network, particularly the left IFG, notably BA 44, selectively supporting the hierarchical computation essential for syntactic composition. MEG findings further corroborate this by revealing frequency-specific cortical tracking of linguistic hierarchies, consistent with merge-based structure building. Although these findings support the neural specificity of external merge, its status as a uniquely human capacity remains contested, as some recursive abilities have also been observed in non-human primates and songbirds, albeit without comparable neural evidence. In contrast, internal merge—responsible for syntactic movement—has received relatively less attention. Evidence from constructions involving displacement (e.g., *wh*-movement, topicalization, passivization, and scrambling) indicates consistent activation in the left IFG. These findings suggest a partially overlapping but functionally differentiated neural basis for internal merge. Importantly, many of these constructions also entail semantic changes, making it essential to control for such confounds in future work.

4 CONCLUSION

This study has sought to bridge the theoretical framework of biolinguistics with empirical neurobiological evidence, systematically evaluating the neural foundations of the FLB and the FLN. Through a critical synthesis of existing neural data, we have demonstrated that the modular architecture of the FLB—encompassing phonological-phonetic, syntactic, semantic, and pragmatic modules—is instantiated in distinct yet interactively coordinated neural circuits. Neuroimaging evidence, particularly from language comprehension studies, reveals a dynamic interplay among these modules, with parallel processing reflecting the flexible yet biologically constrained nature of the human language system. To fully substantiate the integrative design of the FLB, future research must extend beyond comprehension to encompass language production, leveraging lesion studies, behavioral paradigms, and neuroimaging to map the neural correlates of generative processes.

Regarding the FLN, our analysis underscores the neural grounding of merge, the core syntactic operation, centered on the left IFG. This region, particularly BA 44 of left IFG, emerges as a universal neural signature for external merge across languages, while phenomena involving internal merge (e.g., *wh*-movement, topicalization, passivization, and scrambling) similarly engage the left IFG. These findings affirm the biological foundations of hierarchical structure-building as a uniquely human cognitive capacity. Nevertheless, further neurobiological inquiry is warranted to disentangle the precise neural distinctions between external and internal merge. By integrating these insights, this study not only advances our understanding of the neurobiological underpinnings of language but also reinforces the interdisciplinary promise of biolinguistics in unraveling the complexities of human cognition.

Looking ahead, the continued progress of biolinguistics might depend on its ability to incorporate a broader range of interdisciplinary methodologies to rigorously test and refine its core theoretical constructs. Advances in neuroimaging, computational modeling, genetic analysis, and cross-species comparisons offer powerful tools for probing the biological substrates of language with increasing precision. By embracing these approaches, biolinguistics can move beyond abstract theories toward a more evidence-based paradigm, where theoretical insights are continually informed, constrained, and enriched by empirical data. Such integrative efforts will not only clarify the architecture of the faculty of language but also enhance the field's capacity to generate robust, falsifiable models of uniquely human linguistic competence.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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THE CURRENT SITUATION OF NEW MEDIA MARKETING IN CHINESE HIGHER EDUCATION INSTITUTIONS (HEIS): A CASE STUDY BASED ON HEIS IN HENAN, CHINA

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Abstract: In the context of the rapid development of the Internet and new media, marketing communication of HEIs using newspapers, radio, TV, and magazines as traditional media has encountered unprecedented impact, and new media platforms have gradually become an essential carrier of marketing communication HEIs. This paper reviews the advantages and characteristics of new media marketing and its bottlenecks and collects and organizes the marketing communication methods of new media platforms such as microblog, WeChat, and short video in Henan HEIs. Besides, the study analyzed the release contents, release rules and release characteristics of new media marketing platforms of HEIs, and discussed feasible suggestions for HEIs to build a new media communication matrix and expand the communication effect of new media marketing. The study concluded that new media marketing of HEIs should adhere to a holistic way of thinking in content distribution, maintain a high update frequency, improve content creation, strengthen communication effect analysis, continuously train high-quality professionals, and establish a feedback mechanism for public opinion to ensure the effectiveness and efficiency of brand marketing of HEIs. The purpose of the study is to provide a reference for new media marketing of HEIs.
Keywords: HEIs; Marketing; New media; Communication; Branding

1 INTRODUCTION

Traditional media, with newspapers, radio, TV, and magazines as media, have the characteristics of authority, rigor, and authenticity of information release. After years of development and accumulation, traditional media have accumulated rich experience and mature norms in the planning, editing, reviewing, and distributing content and have advantages that are difficult to replace. The brand marketing of HEIs has established a good brand image in the hearts of the general audience in terms of depth, breadth, and height of information with the advantages of traditional media. The marketing effect of traditional media has improved the authority and credibility of HEIs. However, the mobile Internet has broken people's original way of life and changed the way of accessing information, breaking through time and geographical restrictions. Traditional media communication is no longer able to meet people's demands for information acquisition. New media, a product of the information technology revolution, integrate pictures, sound, and video, enhancing the fun of reading and meeting people's needs for fragmented time reading. In addition, new media can realize the audience's independent choice and form an excellent two-way interaction of information, which makes the media and users more sticky. Under the background of mobile Internet, HEIs use new media platforms such as short videos, WeChat, and microblogs as an essential way to disseminate information and brand marketing. New media marketing improves school brand influence, increases school visibility and reputation, enhances internal cohesion and centripetal force, and forms a positive interaction between HEIs and the outside world. This paper intends to analyze the current situation of new media marketing in Chinese HEIs, focusing on the new media of HEIs in Henan Province, China, to provide reference materials for improving the effectiveness of marketing communication systems in HEIs in China the world.

2 LITERATURE REVIEW

New media marketing is an emerging research field, and with the increased attention of scholars to this field, its research scale has shown a trend of the increasing year by year. New media marketing is a new marketing method carried out by the technology of new media platforms [1], which is mainly based on the Internet, mobile media, and digital media technology, and a series of marketing activities such as advertising communication, product promotion and image display under the online marketing platform [2]. The more popular new media marketing platforms are social platforms, electronic publications, and online video platforms [3]. Social media marketing refers to marketing activities conducted by companies using social media such as WeChat, Weibo, and QQ [4]. Online video marketing refers to marketing activities using conventional video platforms (e.g., Youku, Tencent Video, and Akiyip), short video platforms (e.g., Jitterbug, Crypto, and Weishi), and live streaming platforms (e.g., Hu Ya and Douyu) [5]. Marketing subjects can choose one or more new media marketing channels according to their needs, with the help of carriers such as pictures, videos, audio, and text [6], to improve consumers' attention to marketing subjects and marketing messages [7]. New media marketing is more flexible and interactive, breaking through traditional media marketing information dissemination [8]. In addition to this, new media marketing also has a short and wide range of information reception,

comprehensive and accurate audience, and high conversion rate; novel and fragmented content and easy to accept [9-10]. New media marketing can enhance the space for innovation in marketing methods and better shape the company's image, and help create a brand effect [11]. However, new media marketing is also a double-edged sword, and if companies lack control over new media marketing, it can cause more negative problems in the marketing process. Wen shows that enterprises overly focus on marketing and ignore the substantive content of marketing [12], leading to a single means of using new media marketing, thus not entirely playing the effect of new media marketing. In the process of using new media marketing, companies overemphasize the form of the product without giving sufficient assurance to the quality of the product, then the marketing effect is counterproductive [4]. In addition, the flexibility of new media marketing means that its results are arbitrary and uncontrollable. If companies cannot handle negative information correctly, it can also spread rapidly through the new media platform and cause severe losses to the company's interests [13-14].

3 METHODS

Literature review method. By reviewing relevant professional books, Internet and journal work, materials and journal articles, collating and analyzing relevant domestic and foreign literature, obtaining relevant research information, and further organizing, analyzing, and sorting out the obtained information as the most basic information for writing this article.

Case study method. Taking Chinese undergraduate HEIs in Henan Province as an example, we summarize, summarize and analyze the overall situation of new media communication in Chinese HEIs, put forward the experiences and shortcomings in the process of new media communication in HEIs, and provide the information with a reference value for HEIs to better play the effect of new media communication.

4 RESULTS

Traditional media such as TV, school newspaper, and campus radio have long been the main marketing channels of HEIs and the vital information receiving platforms for teachers and students. Facing the strong impact of new media and the reality of media "iteration," HEIs have to adapt to the new situation, focus on the marketing advantages of new media, and reconstruct the new pattern of combining new media and traditional media. At present, the leading platforms of new media marketing for HEIs in China are official microblogs, WeChat public numbers, and short videos (TikTok and Kuaishou), which have gradually become the most mainstream communication vehicles for information promotion, image building, and brand marketing of HEIs in China. This paper collects and organizes the data of official microblog, WeChat public number, and short video platforms of HEIs in Henan, China, and analyzes and discusses the current situation of new media platform marketing of HEIs to provide a reference for new media brand media marketing of HEIs.

4.1 Microblog

Microblog is a platform for sharing, spreading as well as acquiring information based on user relationships. Users can form personal communities through WEB, WAP, and various clients, update information with text, pictures, and videos in about 140 characters and share them instantly, which has the characteristics of fast-spreading, comprehensive coverage, and significant influence. By the end of December 2020, all undergraduate HEIs in Henan Province have opened official microblogs with a total number of fans of about 2.2 million, an increase of 400,000 over 2019. The most significant number of fans is Zhengzhou University, with 640,000 fans. It is followed by Henan University and Xinyang Normal College, with 445,000 and 188,000 followers, respectively (Figure 1).

(1) In terms of fan increment, the number of fans of Henan undergraduate HEIs increased at a steady rate. Zhengzhou University stands out with faster growth in fan size, with an increment of about 170,000 fans in 2020.

(2) In terms of the number of content publications, 59 official microblogs of undergraduate HEIs in Henan Province published 227,200 news in 2020, 63,400 more than that in 2019. The number and originality of microblogs are outstanding, especially the official microblogs of Shangqiu Normal College publish the most news, with a total of 11,322 articles in 2020, with a daily average of 31.07 articles and 7,978 original news, with an originality rate of 73%; followed by Henan University of Traditional Chinese Medicine, with 7,929 articles in 2020 and 7,540 original articles, with an originality rate of 95%; and again by Anyang Normal College, with 6,722 articles were issued in 2020, with 6,619 original articles, and the originality rate reached 98.46% (Figure 2).

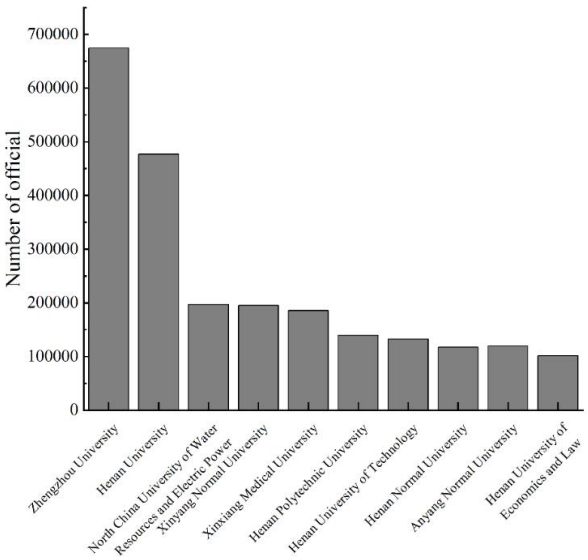

Figure 1 Top 10 Official Microblog Fans of Henan Undergraduate HEIs (From "New Media White Paper of Henan Province Education System 2020")

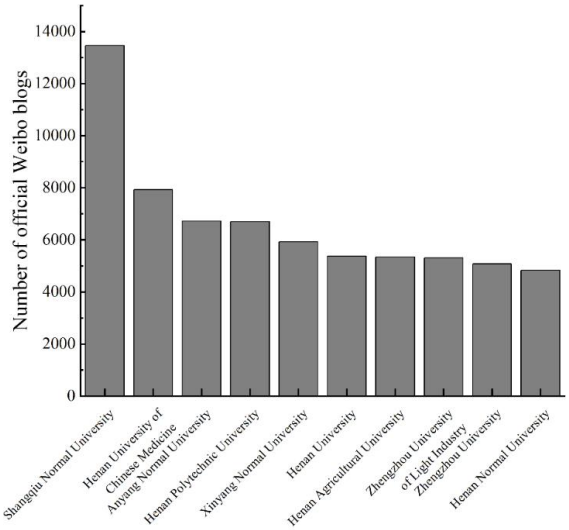

Figure 2 Top 10 Official Microblogs of Henan Undergraduate HEIs (From "New Media White Paper of Henan Province Education System 2020")

4.2 WeChat

WeChat is a chatting tool that can send voice messages, text, pictures, and videos over the Internet, and it has been trendy since it was developed and launched by Tencent in January 2011. By the end of 2014, more than 600 million registered WeChat accounts, with college students in higher education accounting for more than one-third of the total. According to a questionnaire survey conducted by Tencent Micro school and Xinbang on Chinese university students, more than 83% of students in higher education follow campus WeChat public numbers, and more than 80% of them follow more than 3 campuses WeChat public numbers, of which 42% follow 3-5 and 37% follow 6-10. More than half of the students check campus WeChat public websites every day, with 18% of them checking multiple times a day and 32% almost once a day. In addition, 41% of them use it more frequently than once a week. Campus WeChat public websites have been deeply integrated into campus life. Most students view 2-5 articles from campus WeChat public websites on average every day, and the proportion of students who view them for more than half an hour on average every day is nearly 70% (Tencent Microschool, 2019 New Media Observation Report for HEIs). By December 2020, all 59 undergraduate HEIs in Henan Province have opened official WeChat, and the overall operation is regular.

(1) In terms of the WeChat influence index (WCI): the highest WCI is Zhengzhou University with 913.53, followed by Henan University with 888.56. Henan Polytechnic University is in third place with 834.65 WCI.

(2) In terms of the number of releases and the number of articles issued: the total number of releases of 59 official micro letters of Henan undergraduate HEIs in 2020 was 15,750 for the year, which is 10,091 times more than the number of releases in 2019 (5,659). The total number of articles issued was 27394, which was 18,849 more than the total number of articles issued in the whole year of 2019 (8545). Huanghe Science & Technology College issued the highest number of articles with 1,400 articles, or an average of 4 articles per day, followed by Shangqiu Institute of Technology with

1,070 articles. The number of articles issued in 2020 by these two HEIs is higher than the number of articles issued in 2019. In the 2020 year, the official Weibo of Henan undergraduate HEIs with more than 100,000 articles produced 8 articles, including 3 articles of Zhengzhou University, 3 articles of Henan University, 1 article of Henan Agricultural University, and 1 article of Henan Police College (Table 1).

(3) Total number of reads and in-views: Zhengzhou University ranked first in terms of a total number of reads with 6.53 million, followed by Henan Polytechnic University and Henan University with 4.95 million and 4.9 million respectively. Anyang Normal University ranked first with 73,811 in total reads. In addition, Henan University ranked first with the most significant number of in-views of 9,369. Overall, the number of articles read by undergraduate HEIs has improved significantly compared with 2019, and the number of in-views of HEIs has increased accordingly (Table 2).

Table 1 Statistical table of 100,000+ articles on WeChat public websites of undergraduate HEIs in Henan in 2020 (8 articles)

No.	University	WeChat article
1	Henan University	Inside the list! Henan University 52 people rush to Wuhan
2	Henan Agricultural University	Good news| New coronavirus prevention is expected to achieve a quick self-test with one test paper!
3	Zhengzhou University	March! Zhengzhou University's "Retrograde Walkers" are coming to the aid of Wuhan!
4	Zhengzhou University	It is April Day at Zhengzhou University
5	Zhengzhou University	Notice of Zhengzhou University on the return of students in the spring semester of 2020
6	Henan Police College	[Golden List Release] 2020 Henan Police College Public Security Major Early Batch Admissions List
7	Henan University	The alma mater is 108 years old. What do you want to say?
8	Henan University	Briefing!

Note: From "New Media White Paper of Henan Province Education System 2020".

Table 2 Top 10 Official WeChat Influence Index of Undergraduate HEIs in Henan

Top 10	WeChat Public Number	Total number of articles	Total number of reads	Total number of views	Number of posts	Number of headline articles read	Max Reads	Maximum number of views	WeChat influence index
1	Zhengzhou University	454	6530000	73060	444	6480000	100001	6426	913.5356632
2	Henan University	341	4900000	72572	213	4820000	100001	9369	888.5694298
3	Henan Polytechnic University	516	4950000	40114	240	4840000	52479	825	834.6499691
4	Anyang Normal University	364	3170000	73811	364	3170000	73112	613	812.3592865
5	Henan Normal University	442	3130000	38612	193	3040000	92550	1261	788.4833547
6	North China University of Water Resources	409	2740000	34566	194	2644097	59298	645	763.30289
7	Sias University, SIAS	479	3350000	14973	308	2970000	65032	407	758.0267066
8	Xinyang Normal University	397	2370000	30119	396	2370000	31861	623	734.9926244
9	Railway Police College	505	2250000	30703	366	1950000	53649	472	715.8916703
10	Henan University of Technology	376	2010000	18011	291	1920000	53815	2197	713.0455117

Note: From "New Media White Paper of Henan Province Education System 2020".

4.3 Short Videos

Short videos are developed based on the development of mobile Internet, they are disseminated through mobile Internet, following the trend of fragmentation time, and the short, fragmented content dissemination meets users' needs. This entertaining and interactive form of communication is very much in line with young groups and fashion trends.

4.3.1 TikTok

In 2020, 45 of the 59 undergraduate HEIs in Henan Province entered TikTok, 14 new institutions compared to 2019. Four HEIs have TikTok accounts with more than 100,000 followers (Henan Police College, Shangqiu Institute of Technology, Zhengzhou University, Railway Police College). Among them, Henan Police College has 355,000 followers, an increase of 97,000 over the previous year. From July to December 2020, the top ten TikTok likes of undergraduate HEIs in Henan accumulated 119,000 likes, and the number of likes of Shangqiu Institute of Technology was 1.98 million at the top of the list. The highest number of TikTok retweets during July-December 2020 is

Zhengzhou Shengda University, with 11524 retweets. During July-December 2020, Shangqiu Normal University had the highest number of TikTok platform posts and the highest frequency of posts, with 342 short videos posted and a daily average of 1.8. They are followed by Shangqiu Institute of Technology and Xinyang Agriculture and Forestry University, with 240 and 205 releases, respectively. The top 10 official TikTok fans, likes, and releases of HEIs in Henan Province from July to December 2020 are shown in Figure 3, Figure 4, and Figure 5.

4.3.2 Kuaishou platform

As of December 2020, 24 undergraduate HEIs in Henan Province entered the Kuaishou platform, among which 8 official Kuaishou accounts of HEIs have more than 10,000 fans, and 9 official Kuaishou accounts of HEIs have more than 100,000 likes. It is worth noting that Zhengzhou University's Kuaishou platform has more than 180,000 fans, ranking first in the ranking of official Kuaishou fans of HEIs in Henan Province. Between July and December 2020, the Shangqiu Institute of Technology had the highest Kuaishou activity, with 209 short video works published, 56.91 million plays, and 2.605 million likes. By the end of 2020, Shangqiu Institute of Technology's Kuaishou platform had published a total of 738 short video works with 100,000 followers. The top 10 official Kuaishou fans and releases of HEIs in Henan Province are shown in Figure 6 and Figure 7.

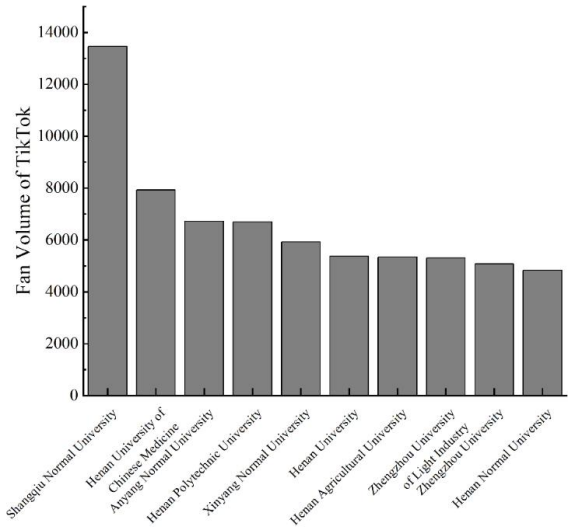

Figure 3 Top 10 TikTok Fans of Undergraduate HEIs in Henan (From "New Media White Paper of Henan Province Education System 2020")

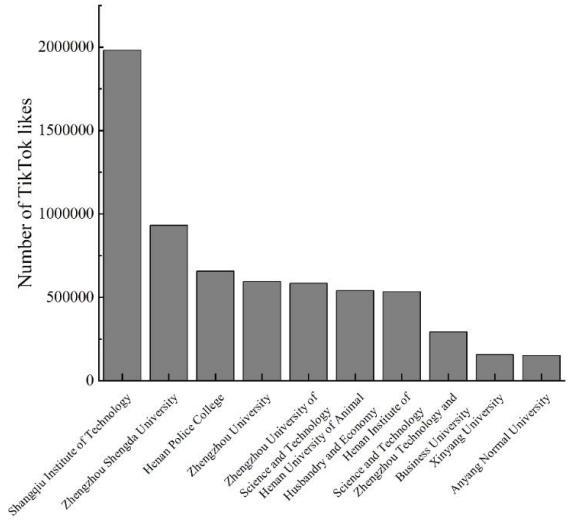

Figure 4 Top 10 TikTok Likes of Undergraduate HEIs in Henan (From "New Media White Paper of Henan Province Education System 2020")

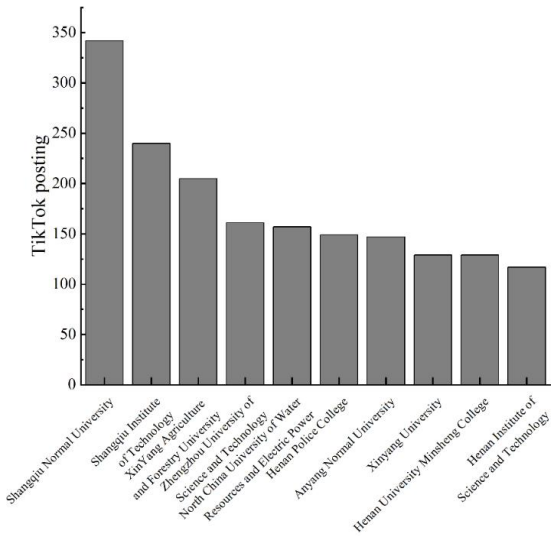

Figure 5 Top 10 of TikTok Posting Volume of Undergraduate HEIs in Henan (From "New Media White Paper of Henan Province Education System 2020")

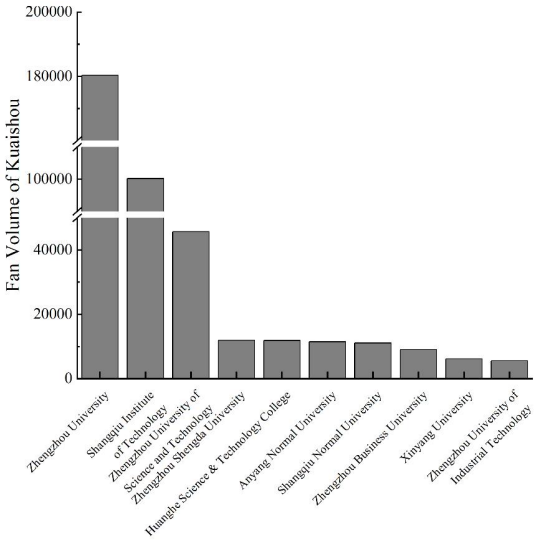

Figure 6 Top 10 Kuaishou Fans of Undergraduate HEIs in Henan (From "New Media White Paper of Henan Province Education System 2020")

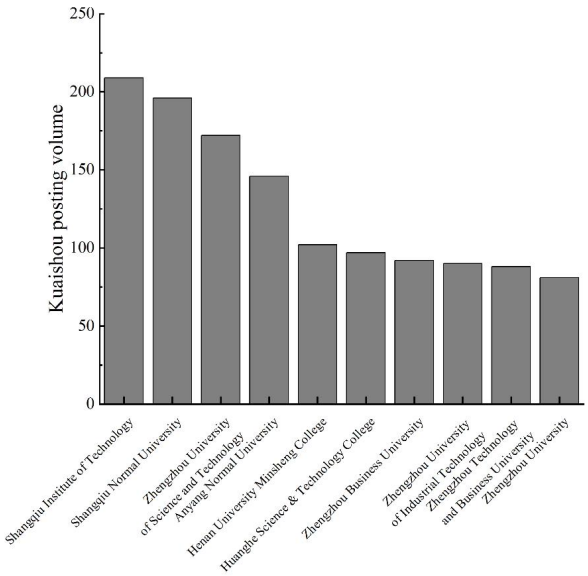

Figure 7 Top 10 Undergraduate HEIs in Henan Kuaishou Posting Volume (From "New Media White Paper of Henan Province Education System 2020")

5 DISCUSSIONS

5.1 Microblog Marketing of HEIs

As a low-cost, high-efficiency, and wide-ranging communication platform, microblogs are open, convenient, and friendly, which helps to bring the university closer to its followers and facilitate them to express their opinions freely. Henan University's official microblog is named "Xiaohe" which personalizes it and uses pronouns to make it more lively. The official microblog of Zhengzhou University is close to the daily needs of students and faculty and speaks for students, both sharply and tenderly, such as posting exciting and hot topics on campus or in the community and inviting students to participate. Henan University of Chinese Medicine microblogging insists on producing interactive topics, good morning and good night topics, interesting stories sharing topics, knowledge sharing topics, campus scenery topics. The text usually ends with questions or interactive expressions, often with naughty emoticons to attract followers' attention and comments. This lively form of interaction with fans is more likely to attract fans and increase attention. In addition to this, the microblog of HEIs can timely, comprehensively, and accurately release the progress of the school's work in talent cultivation, scientific research, social services, cultural heritage, and innovation. Relying on the Weibo platform, teachers and students are organized and mobilized to plan attractive jointly, highly participatory, and interactive online promotional activities to showcase the changes and achievements of the university in promoting economic and social development, with remarkable marketing effects. For example, the official microblog of the Henan University of Chinese Medicine has opened a unique topic of Chinese medicine, highlighting the characteristics of the school, which is conducive to the dissemination of Chinese medicine knowledge and the enhancement of the school's influence. Henan University's official microblog often promotes its century-long university history and humanistic accumulation and increases exposure through daily interaction with other institutions' official microblogs. In general, current Chinese universities can use the interactive and immediacy of Weibo to effectively strengthen communication with the outside world and continue to gather and integrate resources. At the same time, promote teacher-student exchanges and provide services for teacher-student learning and learning to highlight the campus-style and teacher-student spirit and effectively market the university brand.

5.2 WeChat Marketing of HEIs

The flexible and interactive nature of WeChat makes it easier for HEIs to reach their audiences and makes HEIs more "reachable" and impressive. Therefore, WeChat has become one of the most popular and convenient ways for Chinese HEIs to disseminate information, showcase campus culture, promote unique campus content, and interact with students and teachers. Overall, whether the official WeChat activity, the number of posts, or the number of page views and page views of the undergraduate colleges and universities have increased compared with 2019. WeChat postings of HEIs in Henan Province gradually shifted from fewer and more precise to more extensive and better, and the quality of content planning in terms of choosing angles and fitting hotspots has improved. The focus of public number operation is tilted toward creating high-quality, high-quality content. Zhengzhou University's official WeChat article "It is April Day at Zhengzhou University" has achieved more than 100,000 reads. The article was published at an essential point of the new epidemic, depicting the beauty of spring at Zhengzhou University and expressing the determination and confidence of teachers and students to overcome the epidemic. The article is well-titled, choosing the entry point from the audience, hitting the heart, and being highly readable. The concise and compelling text combined with eye-catching illustrations made the article a hit as soon as it was released. The official WeChat of the HEIs releases the accumulated school history, proud school achievements, positive energy-filled role models, and familiar and friendly campus scenery, thus triggering emotional resonance, awakening shared fond memories, and increasing the attention of the public number. The article "Alma Mater is 108 years old, what do you want to say" pushed by Henan University's WeChat platform stood out with 100,000+ reads and 2,102 likes. The article's title is eye-catching, and the main idea of the article is clearly stated while leaving enough space for interaction with fans, which is a prominent marketing effect. In terms of content, the article closely follows the hotspot of "university celebration". It starts from emotions, combining the history of Henan University with the beautiful scenery of the campus in four seasons, expressing the good wishes for Henan University and arousing the resonance of alumni. The strength of this article is that it combines the hot topics at the right time and captures the proper focus of the article. In addition to this, the targeted and phased release of information by HEIs through the WeChat platform to guide the rumor spread can effectively shape the good social image of the university and prevent adverse news events of HEIs from spreading rapidly in a viral way and triggering public opinion crisis [14]. On October 7, 2020, Henan University's official WeChat released the "Information Bulletin" to promptly inform and respond to the adverse events of the university after they had aroused more attention and discussion on the Internet, which prevented further fermentation of public opinion. The article spread quickly after its release, gaining 100,000+ reads, 1,600+ views, and 2,900+ likes. Students, faculty, alumni, and the community were generally concerned and affirmed the university's positive attitude in dealing with such incidents.

In a word, WeChat has become an essential medium for teachers and students to communicate, share and comment on various information in campus life, an essential platform for the public to understand the information of HEIs, and an authoritative platform for branding and image communication of HEIs. The WeChat public website helps HEIs build a good brand image and enhance its popularity, reputation, and social influence through its marketing advantages and high-quality marketing communication content.

5.3 Short Video Marketing for HEIs

According to the "2020 TikTok College Student Data Report" released by TikTok, the number of college student users has exceeded 26 million as of December 31, 2020, accounting for nearly 80% of the total number of college students in China. Based on the high-frequency usage of new media and the great attention to new media information among contemporary students, HEIs have seized the short video windfall, built short video platforms, and strengthened short video operation. 799 HEIs in China have entered new media platforms such as TikTok, Kuaishou, and B Station to enhance interaction with students and launch higher education brand marketing. Comparing the two platforms, TikTok and Kuaishou, Chinese HEIs have more total followers and more significant influence on the TikTok platform, which may relate to the short video platform's audience and promotion efforts. Among the HEIs in Henan Province, Shangqiu Institute of Technology has performed more outstandingly in the marketing operation of short video platforms, entering two short video platforms, TikTok and Kuaishou, and its short video position building has gained strong momentum, with a total of 347,000 fans on the two platforms. The released contents mainly focus on students' daily life, campus food, and school activities, and the scenes are mainly located in the school canteen, playground, classroom, and dormitory. The content is exciting and diverse, primarily responding to the issues and topics of most concern in the daily life of college students. The text is short and exciting, with a fresh style, using storytelling and exciting editing techniques to increase the video's ornamental. It is worthwhile to promote Shangqiu Institute of Technology's official TikTok to other HEIs because it accepts submissions from all students and faculty members and receives works from a wide range of channels, making the platform more diversified. It is worth mentioning the short video "Let your school shoot you" released by Shangqiu Institute of Technology on October 20, which adopts the way of "music stomping clip" and introduces the video through the topic, which organically combines the school and students and reflects the youthful vitality of the students. In addition, using the school's characteristics and advantages to promote the correct values and encourage young people to work hard in the short video platform will also get more likes and retweets. Henan Police College uses TikTok to show the daily training of students and selects the most realistic contents of the school as short video materials to promote the spirit of students and school scenery, which attracts the audience's attention and effectively improves the brand marketing of HEIs.

In general, Chinese HEIs have not paid enough attention to the construction of short videos, and most of them have no or few updates. If short videos can be deeply integrated with other social network media, it can lead to greater exposure of video content on their platforms in other social network media.

The analysis of the results of brand marketing communication of colleges and universities in Henan Province reflects that Chinese colleges and universities attach great importance to the marketing opportunities brought by new media. Colleges and universities are ready to take advantage of the rapid dissemination and interactive linkage of new media to design and produce engaging, interactive content and highlight colleges and universities' brand characteristics through new media platforms such as Weibo, WeChat, and short videos. However, different new media marketing channels will be fragmented without an excellent macro design, and marketing effectiveness will be weakened. Therefore, HEIs should fully integrate all kinds of communication channels, establish all-media thinking, build a new media communication matrix, and expand the new media marketing communication effect. Facing the current situation that new media marketing in higher education is still in the exploration and initial stage, new media marketing in higher education should follow.

First, new media can adopt a holistic way of thinking in content distribution to avoid content re-distribution and omission. Secondly, the new media platform should maintain a specific update frequency to retain the fan ownership rate and make the new media account gain longevity. Thirdly, the new media should improve content creation, fully take advantage of the school's unique talent and intellectual advantage, and produce high quality, high likes, and high spread works on the premise of profound mastery of the new media platform communication law. Fourthly, the new media marketing department of the school should strengthen the analysis of marketing and communication effects and provide new ideas for the next new media selection planning by analyzing the communication channels, communication trends, and reproduction of specific contents. Fifth, it is necessary to train professional talents within HEIs and make full use of big data to enhance the ability of public opinion analysis and build public opinion early warning and feedback mechanisms to ensure that information favorable to the university is quickly and effectively led and negative impacts on the university are dissipated.

6 CONCLUSIONS

In the new media environment, emerging media such as WeChat, micro-blog, and short video have broken the traditional monolithic marketing communication method of HEIs and become one of the most critical channels for HEIs' brand marketing. Making full use of the timely, sharing, and exciting features of new media saves the time cost of brand marketing of HEIs and effectively improves the reach of brand marketing of HEIs. Chinese colleges and universities have made full use of the resource advantages and application characteristics of different new media to continuously optimize their working mechanisms, improve their operational levels, and integrate their strengths. New media in colleges and universities should mainstream information release and public opinion guidance; standardize platform operations and the team of practitioners; carry out various branding activities to take this opportunity to continue to increase user stickiness. Enhancing the communication power of new media strengthens the school brand marketing communication and promotion, thereby improving the influence.

COMPETING INTERESTS

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THE IMPLEMENTATION PATH OF PERSONALIZED FITNESS FOR RURAL ELDERLY EMPOWERED BY INTELLIGENT EXERCISE PRESCRIPTION

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Abstract: This study responds to the call to accelerate the digital transformation in rural areas, and pays special attention to promoting the active and healthy aging of rural elderly. We used generative artificial intelligence (AI) technology to develop and evaluate personalized exercise prescriptions, and planned a digital and inclusive path for rural fitness projects. This study adopts a mixed design method, which combines controlled field experiments, systematic literature review and semi-structured expert interviews. Firstly, a theoretical framework based on evidence is established by synthesizing domestic and foreign literatures. Secondly, experts in the fields of rural public health, sports science and digital health were interviewed to improve the intervention program. Finally, a number of field experiments were carried out in rural communities. Baseline health data were collected from older people living in the community. Then, the generative AI algorithm generates a personalized exercise prescription, which details the exercise mode, intensity, duration, frequency and progress. Participants followed the plan of AI generation and performed 12 weeks of exercise under the supervision and guidance of coaches.
Keyword: Exercise prescription; Generative AI; Rural elderly; Personalized fitness; Rural revitalization

1 INTRODUCTION

Rural populations are ageing rapidly, yet older adults in these settings remain among the least physically active and most underserved by evidence-based exercise services. National policy documents issued in early 2025 identify the digital transformation of rural areas and the promotion of "Healthy Ageing" as strategic priorities, explicitly calling for upgraded information infrastructure and inclusive, technology-enabled public-health solutions. Parallel national fitness and "sports-power" strategies recognize that rural fitness facilities and professional guidance are scarce, while residents' health awareness and scientific exercise knowledge are limited. Against this backdrop, the present study explores whether generative artificial intelligence can provide a personalised, low-cost, and scalable remedy.Field interviews and baseline surveys conducted in rural Shaanxi reveal three dominant barriers: (1) weak exercise awareness—many older adults equate farm labour with adequate physical activity; (2) homogeneous, unplanned exercise modalities such as walking or housework; and (3) a severe shortage of qualified instructors able to deliver safe, individualised programmes. These factors collectively restrict health improvements and increase injury risk.To address these gaps, we developed an open-source, voice-interactive AI device ("Little Teacher") that automatically generates exercise prescriptions from simple health inputs. A three-month, two-arm randomised controlled trial involving 40 community-dwelling older adults (20 per arm) was implemented to evaluate feasibility and preliminary efficacy. Primary outcomes included functional capacity, balance (via lower-limb surface electromyography during single-leg stance and gait tasks), blood pressure, and self-reported exercise adherence. Secondary outcomes focused on user acceptability and social engagement.By integrating policy guidance, user-centred design, and rigorous field evaluation, this study offers the first empirical evidence on the potential of generative AI to deliver personalised, inclusive fitness services in resource-constrained rural settings.

2 RESEARCH OBJECTIVE

2.1 Policy Background

With the rapid development of China's economy and society, rural revitalization has become an important strategic task in the new era. In January 2025, China has issued the "Comprehensive Rural Revitalization Plan (2024-2027)" , which pointed out the direction for rural development. Among them, Article 26 explicitly proposes to accelerate the construction of digital rural areas, improve information infrastructure, implement smart radio and television rural projects, promote the digital and intelligent upgrading of infrastructure, and build a comprehensive information service system[1]. This strategic initiative aims to empower rural development through digital technology, enhance the level of rural public services, and improve the quality of life of rural residents.

2.1.1 Digital transformation

In terms of digital transformation, the "Overall Layout Plan for the Construction of Digital China" proposes to cultivate and strengthen the core industries of the digital economy, and stimulate the innovation vitality of the digital economy. In addition, the "Key Points for the Development of Digital Economy in 2025" clarify seven key tasks[2], covering accelerating the release of data element value, improving data infrastructure systems, optimizing the layout of computing resources, etc., demonstrating China's forward-looking layout of accelerating the construction of a digital power.

2.1.2 Implementation of national fitness strategy and sports power strategy policies

In terms of implementing the national fitness strategy and the strategy of building a strong sports nation, on the one hand, rural fitness facilities still cannot meet the fitness guidance needs of rural people, and there is a serious shortage of professional fitness guidance personnel, which makes it difficult for rural residents to obtain scientific and systematic fitness guidance; On the other hand, rural residents have relatively weak health awareness and fitness concepts, lacking understanding of scientific fitness and preventive health concepts. In this context, this article aims to explore the path of rural fitness towards digitalization and inclusiveness by promoting artificial intelligence (AI) technology and utilizing AI bots. By leveraging the powerful data processing and intelligent analysis capabilities of AI technology, personalized and convenient fitness guidance services are provided to rural residents, promoting the popularization and improvement of rural fitness services.

2.1.3 Comprehensive rural revitalization plan becomes an important strategic task

The comprehensive rural revitalization plan has become an important strategic task. In the process of comprehensive rural revitalization, the health issues of rural residents are increasingly receiving attention. Health is the foundation of rural revitalization[3], however, poverty caused by illness and returning to poverty due to illness are still key issues that urgently need to be addressed. At present, fitness services and health management in rural areas are facing many challenges, and effective solutions are urgently needed to promote the health and well-being of rural residents.

2.2 Background of Requirements

2.2.1 Health needs

Against the backdrop of an increasingly significant trend of population aging, the proportion of elderly population in rural areas is showing a continuous upward trend, and the health issues of elderly people in rural areas have evolved into a widely concerned topic in society. The health status of elderly people in rural areas is not only directly related to their personal quality of life, but also has a profound and direct impact on the economic situation of rural families and the stable development of society. According to relevant statistical data, the health problems of the elderly population in rural areas have to some extent exacerbated the economic burden on families and affected social harmony and stability. However, as of now, the existing medical facilities and service levels are unable to meet the growing personalized health needs of the elderly[4]. At the same time, the coverage of health management services has significant limitations, making it difficult to comprehensively and deeply benefit every elderly person.

2.2.2 Fitness guidance requirements

With the development of society and the improvement of people's health awareness, the demand for health among rural elderly is increasing day by day. However, due to the lack of systematic scientific fitness knowledge and professional guidance personnel, it is often difficult to take practical and effective fitness measures to improve their physical function. Although elderly people in rural areas yearn for personalized fitness programs to meet their aspirations and pursuits for a healthy lifestyle, they face many difficulties in reality. On the one hand, many social instructors lack enthusiasm and initiative in carrying out fitness guidance work in rural areas due to various factors such as work environment, salary and benefits, and transportation convenience, resulting in a serious shortage of rural fitness guidance forces. On the other hand, the lack of guidance resources for rural fitness makes it difficult for the elderly to have a scientific and directional approach during the fitness process, making it difficult to effectively guarantee fitness results. In addition, the supply-demand contradiction of fitness resources is gradually becoming prominent, and many elderly people in rural areas find it difficult to enjoy high-quality fitness guidance services[5].

2.2.3 Personalized needs

With the gradual improvement of people's living standards and the continuous transformation of health concepts, the fitness needs of rural elderly have gradually shifted from simple physical activities to a more personalized and precise direction. However, there are obvious shortcomings in the current rural fitness service market in meeting the personalized fitness needs of the elderly, mainly reflected in the following aspects: firstly, the homogenization of fitness facilities and services is quite serious, making it difficult to meet the differentiated needs of different types of elderly groups; Secondly, fitness instructors lack a deep understanding and comprehensive consideration of individual physical conditions, interests, and hobbies of the elderly.When formulating fitness plans, they often adopt a "one size fits all" approach, resulting in poor fitness results and even potential harm to the elderly's bodies.

2.3 Application Value

2.3.1 Health benefits

Generative artificial intelligence exercise prescriptions provide scientific and personalized fitness programs for rural elderly people, effectively improving their overall health status by preventing chronic diseases, improving physical

fitness, and enhancing immunity. This not only improves the quality of life for the elderly[6], but also reduces the medical burden on families and society, promoting harmony and stability in rural society[7].

2.3.2 Optimization of fitness services

Effectively solving the problem of a shortage of professional fitness instructors in rural areas, providing convenient and efficient fitness guidance services for the elderly. By generating personalized exercise prescriptions, it meets the fitness needs of different elderly people and improves fitness effectiveness. At the same time, the combination of online and offline models has made fitness services more popular, enhancing the enthusiasm and participation of the elderly in fitness.

2.3.3 Enhancement of rural community vitality

Promoting generative artificial intelligence exercise prescriptions and encouraging more elderly people in rural areas to participate in fitness activities has enhanced their social interaction and sense of community belonging. The popularization of fitness activities has promoted the cohesion and vitality of rural communities, enriched the spiritual and cultural life of the elderly, and helped to build a more harmonious and active rural community environment.

2.3.4 Promoting rural development

The promotion and application of generative artificial intelligence exercise prescriptions have promoted the development of fitness in rural areas and become an important component of comprehensive rural revitalization. It not only focuses on the health needs of the elderly, but also lays a solid foundation for sustainable development in rural areas by improving their quality of life and happiness. In addition, the application of this technology may also drive the development of related industries, such as fitness equipment manufacturing, health management services, etc., injecting new vitality into the rural economy[8].

3 RESEARCH METHOD

3.1 Expert Interview Method

Invite experts in rural fitness, artificial intelligence technology, geriatrics, sports science and other related fields to conduct interviews.

3.2 Experimental Method

3.2.1 Experimental design

This study adopts a randomized controlled experimental design to evaluate the application effect of generative artificial intelligence (AI) exercise prescription in rural elderly fitness using a scientifically rigorous method. The experimental site was selected in Huxian County, Xi'an City, Shaanxi Province. A total of 40 healthy rural elderly people without major exercise contraindications were recruited as research subjects and randomly divided into an experimental group and a control group, with 20 people in each group. The elderly in the experimental group received generative AI exercise prescription guidance, while the control group received traditional fitness guidance services. The experimental period is set at three months to ensure that the long-term effects of exercise prescription on the physical function of elderly people can be fully observed.

3.2.2 Data collection

Before, during (every two weeks), and after the experiment, comprehensive health data was collected from two groups of elderly people to dynamically monitor changes in their physical functions. The collected physical function indicators include: height and weight; Blood pressure and heart rate; Balance ability; Exercise habits include weekly exercise duration, frequency, and type of exercise. Considering that the main health risk faced by the elderly is the risk of imbalance caused by decreased balance ability, we focused on collecting lower limb electromyography data from 40 rural elderly people. Using a surface electromyography meter, electrodes are placed on the four key muscle areas of the elderly, namely the quadriceps, tibialis anterior, gluteus maximus, and gastrocnemius, to perform authoritative balance tests such as single leg standing, eye closed single leg standing, and vestibular gait. The electrical signal activity of the muscles is recorded to reflect their activation and coordination, providing objective basis for evaluating balance and motor control abilities. Conduct experimental data analysis and comparison to draw conclusions.

3.3 Literature Review Method

3.3.1 Literature collection

Collect literature on rural elderly fitness, generative artificial intelligence, exercise prescriptions, and other related fields through domestic and foreign academic databases such as CNKI, Wanfang Data, PubMed, Web of Science, etc. Focus on recent research achievements to ensure the cutting-edge and scientific nature of the research[9].

(1) The current situation and problems of fitness among elderly people in rural areas

Rural elderly people have a high enthusiasm for participating in sports activities, but their cognitive level is limited. Most people believe that daily labor can replace physical exercise, and their understanding of the difference between sports activities and daily physical activities is insufficient. The construction of fitness service system for rural elderly faces many challenges, including a shortage of professional and technical talents, ineffective policy implementation, uneven resource allocation, outdated infrastructure, single sports activity content, and low participation rate. In addition, most elderly people in rural areas suffer from chronic diseases and require more health attention and assistance[10].

(2) Policy background and strategic significance
The "Healthy China 2030" Plan Outline proposes to comprehensively improve the health level of the people, clearly promote sports activities for key populations, and the health status of rural elderly people as a special group is of great significance for achieving the Healthy China strategy. The rural revitalization strategy emphasizes the importance of farmers, and middle-aged and elderly people in rural areas are the main force in agricultural and rural development, as well as the key group to cope with population aging and promote healthy aging development[4].
(3) Technology and Mode Innovation
The construction of "FIT SCRIPT" proves the necessity of introducing artificial intelligence in the formulation of exercise prescriptions. Its research and development provide a new approach for the field of exercise prescription research, breaking traditional thinking patterns, enhancing system capabilities, and expanding application scope The public health services of the "integration of sports and medicine" model in the community can not only improve the health level of residents, improve their lifestyle, reduce medical expenses, but also have a profound impact on deepening the development of national health. The application prospects of artificial intelligence in the field of national fitness are broad, and the integration of artificial intelligence into exercise prescriptions is of great significance in promoting the high-quality development of national fitness[11].
(4) Development process and optimization path
The intelligent exercise prescription has gone through the initial stage of development, the rising stage of development, and the comprehensive development stage. In its development process, policies and regulations provide the basic basis, interdisciplinary studies provide innovation drive, and healthy upgrading provides endogenous motivation.
The promotion of national fitness development through intelligent exercise prescriptions faces practical challenges such as slow policy and regulatory follow-up, insufficient independent technological innovation, and a disconnect between market mechanisms and user needs The optimization path includes refining and improving policies and regulations, and leveraging institutional support and guidance; Vigorously developing intelligent technology and strengthening the driving role of technological innovation; Focus on user needs and activate market regulation.

4 RESEARCH CONTENT

4.1 Analysis of the Fitness Status and Problems of the Elderly Population in Rural Areas

This study conducted an in-depth investigation of the fitness status of elderly people in rural areas using interview methods, and conducted a detailed analysis from multiple dimensions such as health status, exercise habits, fitness awareness, and behavior. Research has found that there are many urgent problems that need to be solved in terms of fitness among the elderly population in rural areas. Firstly, the awareness of fitness is relatively weak, and most elderly people generally believe that daily agricultural labor is sufficient to replace physical exercise, resulting in insufficient understanding of the importance of scientific fitness and a lack of willingness to actively participate in fitness activities. Secondly, the fitness methods are relatively single, mainly focused on a few forms such as walking and simple household chores, lacking rich diversity and scientific systematic planning, making it difficult to achieve comprehensive physical exercise effects. Thirdly, there is a lack of professional scientific guidance. Due to the shortage of professional fitness instructors in rural areas, elderly people find it difficult to obtain personalized fitness advice that suits their physical condition. This not only leads to insufficient fitness results, but also may face the risk of sports injuries due to inappropriate exercise methods. The above problems seriously restrict the in-depth development of fitness activities for elderly people in rural areas, and hinder the further improvement of their health level.

4.2 Feasibility Analysis of Introducing Generative Exercise Prescription

4.2.1 Connotation, value, and function of intelligent exercise prescription
Intelligent exercise prescription is a personalized exercise plan developed with advanced artificial intelligence technology, based on various factors such as individual physical health data and fitness needs. Its core value lies in being able to fully meet the personalized fitness needs of rural elderly people. By scientifically and reasonably arranging various elements such as exercise types, intensity, and duration, it provides accurate and effective fitness guidance for the elderly, thereby improving fitness effectiveness, reducing exercise risks, and playing an important role in improving their physical function and overall health status.
4.2.2 Technical advantages
(1) Building inclusive generative AI technology
We have carefully built a universal AI Bot device called 'Little Teacher' using open-source programs. The 'Little Teacher' has convenient voice interaction function, which can quickly generate personalized exercise prescriptions that accurately match the physical condition of elderly people based on their personal health data and fitness preferences. During the experimental phase, a total of 40 representative rural elderly individuals were recruited and a 3-month practical application experiment was conducted. During this period, the accuracy, reliability, and feasibility of the experimental equipment were comprehensively verified through regular follow-up visits and continuous monitoring of health data. The experimental results show that the exercise suggestions provided by the "little teacher" have high scientific and precise accuracy, and the operation process is simple and easy to implement, which is very suitable for the operating habits of the elderly and easy to accept and use by rural elderly people.
(2) Explanation of Technical Advantages

Low cost and easy to promote; Excellent interactive experience; Easy to operate and user-friendly; Customized Service Personalization.

4.2.3 Feasibility analysis of empowering fitness

Based on the technical advantages of the intelligent exercise prescription mentioned above and the preliminary experimental verification results, we will conduct an in-depth analysis of its potential and feasibility for large-scale application in the field of fitness for elderly people in rural areas. From a technical perspective, its underlying architecture is stable and reliable, with the ability to respond to complex and changing rural environments as well as the diverse fitness needs of the elderly; From an economic perspective, the advantage of low cost makes its widespread promotion in rural areas feasible and will not impose excessive economic burden on rural families or related fitness service institutions; From the perspective of social acceptance, the good interactive experience and simple operation method make it easy for rural elderly people to accept, thus laying a solid foundation for the comprehensive promotion of intelligent exercise prescriptions in rural areas.

4.3 Ways to Implement Personalized Pathways

Based on the fitness status and demand characteristics of the elderly population in rural areas, as well as the technical features of intelligent exercise prescriptions, we will explore and systematically plan multiple effective ways to achieve personalized fitness guidance paths. On the one hand, by further optimizing the algorithm model of the "Little Teacher" AI Bot, its analysis accuracy of elderly health data and the degree of customization of exercise prescriptions can be improved, so that it can more accurately fit the unique physical condition and fitness goals of each elderly person; On the other hand, we will strengthen cooperation with rural grassroots medical institutions and fitness organizations, build a sound health management and fitness service system, and achieve the organic integration of intelligent exercise prescriptions and offline professional fitness guidance services. For example, grassroots medical staff can assist in collecting health data of the elderly and conducting preliminary physical condition assessments. Then, personalized exercise prescriptions can be generated by "little teachers". At the same time, professional fitness instructors can be regularly organized to conduct offline guidance activities in rural areas to supervise and correct the exercise execution of the elderly, ensuring the safety and effectiveness of fitness activities. In addition, it can also make full use of mobile Internet technology to build an online fitness communication platform, encourage the rural elderly to share their own fitness experience and experience on the platform, promote mutual communication and learning among the elderly, create a good fitness atmosphere, further improve the enthusiasm and initiative of the elderly to participate in fitness activities, so as to jointly explore a practical and feasible personalized fitness guidance path for the rural elderly, and help the rural elderly to comprehensively improve their health level.

5 CONCLUSION AND SUGGESTIONS

5.1 Completion Status of Research Work

This study focuses on the fitness issues of elderly people in rural areas, using interview methods to investigate the current status of fitness. Key issues such as weak fitness awareness, single methods, and lack of scientific guidance were found. To address these issues, a "Little Teacher" AI Bot device was built and a [specific duration] experiment was conducted to collect and analyze health data. The experimental results show that the "Little Teacher" device can effectively improve the fitness effect of the elderly, enhance their health status, and increase their fitness enthusiasm and participation. Through intelligent exercise prescriptions, elderly people can receive personalized fitness guidance, reduce exercise risks, and promote the improvement of their health level. This study applies generative AI technology to the fitness field of elderly people in rural areas, providing solutions to the problem of insufficient fitness guidance and promoting the popularization of fitness services.

5.2 Suggestions Based on This Study

Continuously optimize the 'Little Teacher' device to improve data accuracy, interactive experience, and personalization level. Based on the actual situation in rural areas, develop more suitable universal exercise suggestions and health guidance functions. Collaborate with grassroots medical institutions and fitness organizations to promote intelligent exercise prescriptions. The government and community should strengthen publicity, provide training, encourage more elderly people to use equipment, and enhance health awareness.

The government will increase funding support and encourage the research and development of low-cost equipment. Establish a monitoring mechanism, track application effectiveness, and provide timely feedback and adjustments.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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EXPLORATION OF THE AESTHETIC VALUE OF DECORATIVE PATTERNS IN LINGNAN RESIDENTIAL BUILDINGS DURING THE MING AND QING DYNASTIES

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Abstract: The Ming and Qing dynasties was the golden age of Lingnan architecture development, and the architectural patterns of Lingnan folk houses showed rich diversity of natural motif pedigree, humanistic image cluster and comprehensive pattern. These patterns are a combination of plants, animals, geometric shapes and human figures, which not only have a high degree of artistry, but also contain profound symbolic significance. In terms of design concept, they realize the harmonious unity of formal beauty and functional beauty, the perfect blend of natural beauty and humanistic beauty, and the deep integration of regional characteristics and national culture, vividly demonstrating the Lingnan people's yearning for a better life and deep emotion for traditional culture, and providing historical reference for the concept of "remembering nostalgia" in contemporary urban and rural construction. To provide theoretical support for the inheritance of Lingnan architectural cultural heritage. Digging deeply into its cultural implication and exploring the way of integration with modern life will promote the innovative development of traditional aesthetics and modern design, contribute to the deep integration of cultural inheritance and modern design, and promote the inheritance and development of Lingnan architectural art in the new era.
Keywords: Ming and Qing dynasties; Patterns of Lingnan residential buildings; Aesthetic value; Cultural inheritance

1 INTRODUCTION

Architectural patterns, as an integral part of architectural culture, are not only the external manifestation of architectural decoration but also material carriers of regional culture, social concepts, and aesthetic consciousness. The Ming and Qing dynasties marked a golden age for Lingnan architecture. During this period, the Lingnan region experienced economic prosperity, cultural flourishing, and vigorous architectural development. An in-depth study of the aesthetic value of architectural patterns in Lingnan residential buildings during the Ming and Qing dynasties contributes to a comprehensive understanding of the historical and cultural context of the Lingnan region, offering valuable insights for contemporary architectural creation and cultural inheritance[1]. Furthermore, in the context of globalization, the deep exploration and research of local architectural culture holds significant importance for preserving cultural diversity and enhancing ethnic cultural identity.

2 THE GENERATIVE MECHANISM OF PATTERNS IN HISTORICAL CONTEXT

The architectural patterns of Lingnan residential buildings during the Ming and Qing dynasties bore witness to historical evolution and transformation. From the relatively simple geometric patterns of the early period to the increasingly complex decorative motifs of later times, these changes not only directly reflected the socio-economic development of the Lingnan region but also embodied shifts in aesthetic perceptions.

2.1 Geographical and Climatic Characteristics

Lingnan's hot and rainy climate directly influenced the structural forms and material selection of decorative patterns. For instance, the ice crack patterns of oyster shell windows in the Pearl River Delta served both ventilation and decorative functions. The Chaozhou anti-weathering ceramic mosaic technique utilized the reflective properties of ceramic tiles to create unique light and shadow effects during the rainy season. This "adaptation to natural conditions" creative thinking transformed environmental factors into intrinsic drivers of artistic innovation.
Lingnan’s humid and hot climate necessitated that architectural pattern designs prioritize moisture resistance and ventilation. Lime sculpture and brick carvings were commonly used for exterior wall decorations due to their excellent thermal insulation and moisture-proof properties. Lime sculpture, with their unique material formulations and craftsmanship, remained stable in humid environments, effectively preventing wall damage. Brick carvings, through their special structures and materials, partially blocked heat from entering indoor spaces, providing cooling effects. For example, in many traditional Buildings in Guangzhou, Lime sculpture and brick carvings on exterior walls have remained intact through the ages, maintaining a relatively comfortable indoor environment, as shown in Figure 1.

Figure 1 Qingzhen Building and Main Hall of Foshan Ancestral Temple [2]

2.2 Multicultural Integration

Lingnan's unique cultural traditions profoundly influenced its architectural decorations. As an important component of Chinese historical culture, Lingnan culture inherited the essence of Central Plains culture while integrating local and overseas elements, forming a distinctive cultural tradition. During the Ming and Qing dynasties, Lingnan residential architectural patterns actively absorbed the stylized language of Central Plains architectural decoration and localized it. For example, the "Double Phoenixes Facing Peonies" ceramic mosaic pattern in the "Four-Point Gold" residences of Chaozhou adhered to the compositional principles of the Yingzao Fashi (Treatise on Architectural Methods) while incorporating ecological elements unique to Lingnan, such as the curved grass-tail patterns derived from banyan roots. The "Fisherman, Woodcutter, Farmer, and Scholar" Lime sculpture in the Chen Clan Ancestral Hall in Guangzhou harmonized realism and decoration through geometric patterns like radial rice ears. These examples demonstrate that Lingnan patterns innovated with regional characteristics while inheriting traditional Central Plains art.

The prosperity of the Maritime Silk Road facilitated cross-cultural exchanges and integration, profoundly impacting Lingnan residential architectural patterns and driving the localization of foreign crafts. For example, the cast-iron scrolling leaf window grilles of the Kaiping Watchtower transformed Baroque-style volutes into banana leaf forms. The Corinthian acanthus motifs on Chikan arcade columns were reinterpreted by local artisans into longan and lychee patterns. The enamel pigments introduced through the Thirteen Hongs trade significantly enhanced the color saturation of Cantonese Lime sculpture, forming an aesthetic characterized by "gorgeousness without vulgarity."

During the Ming and Qing dynasties, the rise of the clan system endowed architectural patterns with the function of maintaining familial ethics and hierarchical order. For instance, the Ming Dynasty "Five Relationships" woodcarving in the Shunde Bijiang Golden Tower symbolized the order between monarch and subject, father and son, husband and wife, brothers, and friends through phoenixes, cranes, mandarin ducks, wagtail birds, and orioles, aligning with the Kaogong Ji's (Artificers' Record) concept that "all crafts are the works of sages." Additionally, the "Two First-Class Scholars" brick carvings in Cantonese ancestral halls, combining crabs (jia) and reeds (lu) through homophonic symbolism,symbolizing the culture of imperial examinations in architectural space reflects the profound influence of ritual culture on architectural decorative patterns. Such patterns not only beautified the buildings, but also conveyed the importance that the society at that time attached to the order of the family and the achievements of the imperial examinations. The cultural function of Lingnan architectural decoration is not static, but is constantly developing and changing. With the development of the society, new cultural elements are continuously incorporated into the architectural decoration, making the Lingnan architectural decoration a mirror reflecting the social changes. This cultural continuity and innovation are an important reason for the vitality of Lingnan architectural decoration.

2.3 Socio-economic Impacts

During the Ming and Qing dynasties, Lingnan's economic development and unique geographical environment provided necessary conditions for the flourishing of architectural patterns. From the mid-Ming period, Lingnan's "single-port trade" system significantly advanced the maturation of craft systems like Foshan stoneware and Chaozhou woodcarving. According to the Foshan Zhongyi Township Records, during the Jiajing era, the stoneware industry employed over 10,000 workers, laying a solid foundation for the mass production of architectural decorations. Meanwhile, maritime trade introduced foreign materials such as Southeast Asian hardwoods and Persian glass, enriching the textural diversity of architectural decorations. For example, the Bogu patterns on the main ridge of wok-ear houses and the ice crack patterns of oyster shell windows exhibited diverse material effects due to these imported materials.

Commercial prosperity in the Pearl River Delta during the Ming and Qing dynasties spurred the emergence of auspicious patterns. The traditional Chinese domestic architecture patterns of this period were not only key elements in decorating the buildings, but also contained a wealth of commercial allegory and symbolism.These symbolic patterns reflected the aesthetic trends of the time and also conveyed the yearnings for a better future or future prospects. The commercial prosperity of the Pearl River Delta during the Ming and Qing dynasties spawned the emergence of numerous auspicious motifs.For example, dragon pattern, as a symbol of imperial power, represents power and wealth in commercial activities, and is often used to decorate store fronts or commercial buildings in order to attract customers and highlight the store's eminent status. The scene of "customers like clouds (meaning that there are many merchants as dense as clouds)" in the ceramic spine decoration of the Ancestral Temple in Foshan vividly demonstrates the pomp and circumstance of the activities of the merchant gangs, while the "Five Bats at the Door" tile layout (using the homophonic association of "bat" (fu) with "fortune") on wok ear houses implied the pursuit of wealth and blessings. This creative concept of using patterns to express auspicious meanings fully reflects the value orientation of civil society.

The architectural patterns of Ming and Qing Lingnan were products of geographical environment, clan systems, commercial development, and overseas trade [3]. Their artistic forms carried the genetic codes of Central Plains ritual culture while showcasing creative transformations of foreign elements, ultimately forming a regional aesthetic system characterized by "harmony in diversity."

3 TYPOLOGICAL ANALYSIS OF THE PATTERN SYSTEMS

3.1 Natural Mother Theme Genealogy

Lingnan folk houses architectural patterns are good at combining natural beauty with humanistic beauty in their creation. The plant motifs in Lingnan folk houses are extremely rich, covering a variety of common plants such as lotus, peony, pine and cypress, bamboo, plum blossom and so on. In the actual architectural decoration, these plant motifs are presented through a variety of techniques such as wood carving, stone carving, brick carving and color painting. For example, in the Yuyin Mountain House in Panyu, the wood carving decoration of the lotus flower is delicate, with the texture and form of the petals vividly showing the gracefulness of the lotus flower;And in the brick carvings of the Ancestral Temple in Foshan, the peonies are full of form and bright colors, and the rich and noble image of peonies is shown to the fullest through clever composition and exquisite carving skills.Different plant motifs have different forms, and each of them carries a specific symbolic meaning, adding natural vitality and artistic beauty to the building.

Animal patterns in Lingnan folk houses are equally colorful, with animal images such as dragons, phoenixes, lions, deer, cranes and bats appearing frequently. These animal patterns are vivid and realistic in modeling, showing unique charms through different postures and movements. For example, in the wood carving decoration of the Chen Ancestral Hall, the dragon pattern is robust, with a sinuous and coiled body, detailed carving of scales, and flowing whiskers, as if about to soar in the sky; while the phoenix pattern is elegant, with beautifully carved feathers, showing the beauty and nobility of the phoenix. Deer, harmonic "Lu (emolument)", symbolizing longevity and good fortune, often combined with other auspicious elements in architectural decoration, expressing people's expectations for a better life. Crane, often paired with pine, symbolizing longevity and elegance, in some garden buildings, the emergence of the crane pattern to create a secluded, elegant atmosphere.

Geometric patterns in Lingnan residential architecture include Hui pattern, ice crack pattern, Ruyi pattern and so on. With its continuous lines, Hui pattern forms a simple and rhythmic pattern; ice crack pattern imitates the texture of natural ice cracking, which seems to be irregular but contains the beauty of nature; Ruyi pattern looks like Ruyi, with smooth lines and beautiful modeling. These geometric patterns through a combination of different lines and shapes, in the architectural decoration present a colorful effect. In the Kaiping Watchtower architectural decoration, back to the pattern is often used for doors and windows of the border decoration, enhancing the sense of line and order of the building; ice crack pattern is widely used in some of the garden architecture of the design of the window lattice, creating a unique visual effect. Geometric patterns have unique symbolic meaning, such as the return pattern means auspicious and long, and its continuous lines symbolize endless life and longevity, reflecting people's hope for a better life for a long time Symbolism for the geometric pattern gives a deeper cultural connotation, so that it is not only a kind of decorative elements in the architectural decorations, but also a carrier of people's emotional support[4].

3.2 Humanistic Imagery Cluster

The patterns of human figures in Lingnan architecture cover characters in myths and legends, historical figures, and characters in folk tales. These figure patterns vividly show rich character images through different shapes and expressions. For example, in the mural paintings of the Leizu Temple in Leizhou, the life story of Leizu Chen Wenyu is depicted, with lifelike characters and details of costumes and movements, showing the superior painting skills at that time. In the wood carving decoration of some ancient residential buildings, there is often images of characters from myths and legends, such as the scene of the Eight Immortals crossing the sea, and each character's demeanor and movements are distinctive.

The "deer and bamboo in the same spring (idiom,means deer play and eat bamboo in the spring sunshine, showing the vitality of nature)" stone carving, which is common on the walls of Hakka Dragon House, builds a symbolic system of "family and country together" through the homophonic metaphor of deer (Lu), bamboo (Zhu), and paulownia tree

(Tong). The Lime sculpture of "Fishing, Woodcutting, Plowing and Reading" in the Chen Clan Ancestral Hall in Guangzhou not only realistically reproduces the production scenes recorded in the Tian Gong Ka Shi, but also displays a unique modeling language through geometric patterns such as the hexagonal shape of fishing nets and the radiating shape of rice ears. The figure motifs also have profound symbolic meanings. The Eight Immortals pattern symbolizes longevity and good fortune. Each of them possesses unique magic treasures and magical powers, and is regarded as a deity capable of bringing auspiciousness and blessings, appearing in architectural decorations to express people's prayers for a long and healthy life, happiness and peace. Three Stars of Fortune and Longevity Patterns symbolize good fortune, official fortune and longevity. The images of the three stars usually appear in the main halls or important positions of the buildings, signifying a happy and contented family, a smooth career and prolonged longevity, reflecting people's pursuit of and aspiration for a happy life.

3.3 Composite Patterns

Composite patterns in Lingnan architecture combine a variety of elements such as plants, animals, and geometry to create a complex and varied decorative effect. These composite patterns often blend different elements to complement each other through skillful composition and design. For example, in the architectural decoration of Dongguan Ke Yuan, there are patterns that combine plum blossoms, magpies and geometric lines to form a unique picture. The lofty and unyielding character of plum blossoms, the auspiciousness of magpies and the sense of order of geometric lines reflect each other, showing a unique artistic charm. The comprehensive pattern conveys richer symbolism through the combination of different elements. “Deer and crane in the same spring (idiom,means Deer and cranes play and feed in the spring sunshine, showing the vitality of nature)” pattern combines the symbolism of deer and crane, with the deer symbolizing longevity and good fortune and the crane symbolizing longevity and elegance. The pattern signifies the revival of all living things, full of vitality, and expresses people's desire for a better life and their love for nature.

In addition, there is the paradigm of East meets West, Kaiping Watchtower scroll pattern iron window, in the Rococo scroll on the basis of the integration of the Lingnan banana leaf form; Chikan Riding House Column head of the Corinthian acanthus pattern, after being transformed by local craftsmen, it presents styles of local plants such as longan and lychee. This cultural translation phenomenon fully confirms Chen Yin Ke's strategy of "avoiding the name and living in the real world, taking the pearl and returning it to the casket", reflecting the openness and innovativeness of the Lingnan region in cultural exchanges.

To summarize, Lingnan architectural patterns show a rich diversity in modeling, covering a variety of types such as plant, animal, geometric, figure and composite patterns, each of which contains a wealth of specific motifs. At the same time, these patterns contain profound symbolism behind them, involving people's aspirations for a better life, the importance of family heritage, and the pursuit of moral cultivation. Lingnan architectural patterns are a concentrated manifestation of the history and culture, folk customs and aesthetic concepts of the Lingnan region, showing the concept of harmonious coexistence between man and nature, as shown in Figure 2.

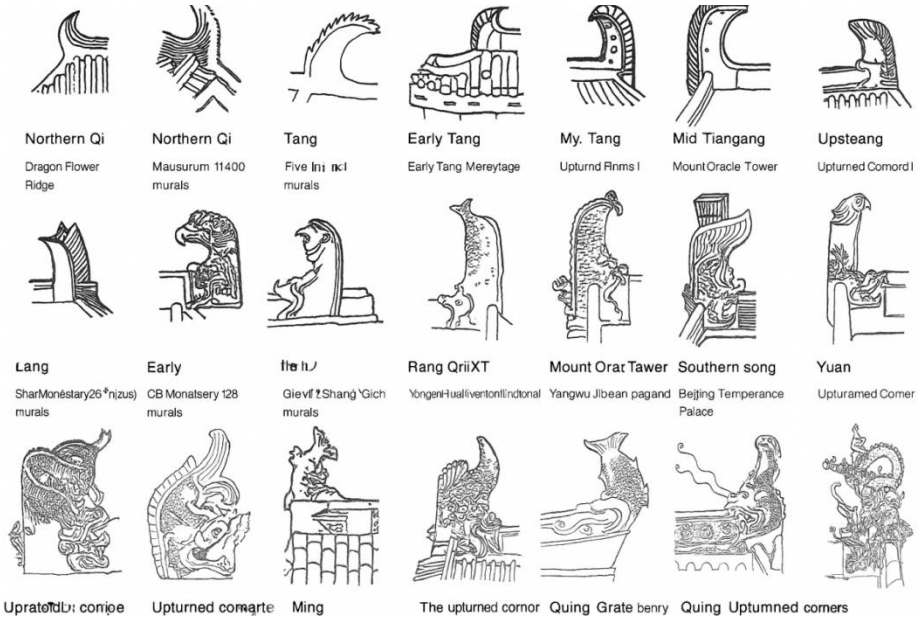

Figure 2 The Formation of Gourd Kisses in Various Dynasties [5]

4 THEORETICAL ANALYSIS OF AESTHETIC VALUE

4.1 Unity of Formal Beauty and Functional Beauty

Lingnan residential architecture pattern in the design of the design focuses on the unity of form and function. Ventilation openings in Lingnan buildings are often designed as exquisite lattice patterns, which not only satisfy the

need for ventilation, but also add to the artistic beauty of the building. Lingnan residential architectural patterns show artistic attainments in modeling and decorative techniques, the wok ear house of the Guangfu architecture, for example, the design of the mountain wall resembles a wok ear, the shape not only has a high aesthetic ornamental, presenting a generous and beautiful visual effect, but also by virtue of the unique form of a strong visual impact. Analyzed from the perspective of aesthetics, this design embodies symmetry and hierarchy, and its shape symbolizes the two ears of the official hat, implying the meaning of being the leader , reflecting the reflection of the social culture of the time in the form of architecture.

Lingnan residential architectural motifs are not only decorative, but also have significant functionality in actual use. The design of the wok ear house is both aesthetic and practical, and studies have shown that its unique shape facilitates the air circulation, provides good ventilation, and to a certain extent is fireproof, which fully demonstrates the perfect fusion of form and function. The layout and structure of Chaoshan houses are designed according to the local hot and humid climate conditions, which is conducive to ventilation and heat dissipation as well as moisture and humidity prevention, reflecting the precise adaptation and deep understanding of the building to the natural environment, which is a vivid practice of functional beauty in architecture. As an important part of Lingnan architectural culture, Lingnan architectural patterns vividly demonstrate the perfect unity of formal beauty and functional beauty with its unique design concept and exquisite craftsmanship, as shown in Figure 3.

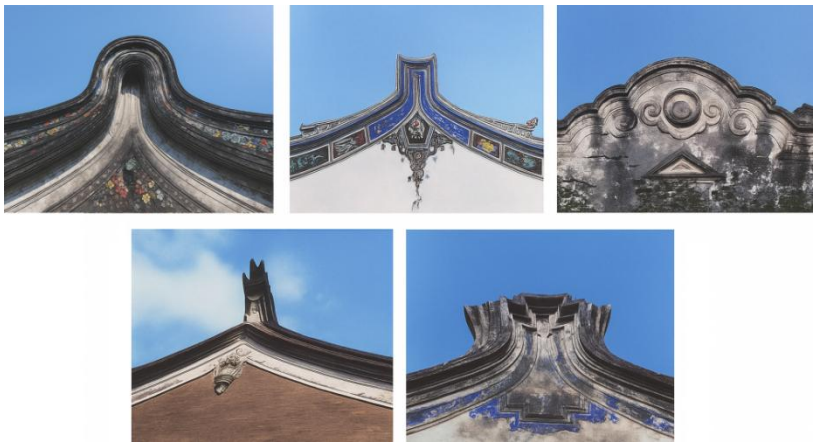

Figure 3 Five Elements Gables of Metal, Wood, Water, Fire, and Soil [6]

4.2 Fusion of Natural Beauty and Humanistic Beauty

Lingnan architectural patterns are good at combining natural beauty and humanistic beauty in their creation. For example, the plant pattern in Lingnan architecture not only imitates the form of natural plants, but also gives the plant pattern a symbolic meaning, reflecting the concept of harmonious coexistence of man and nature. Research on the integration path of natural beauty and humanistic beauty in Lingnan architectural patterns, Lingnan architectural patterns, as an important carrier of regional culture, have formed a high degree of integration of natural aesthetics and humanistic connotations over a long period of time through the analysis of typical cases of traditional architectural decorations in Lingnan, combined with the regional climate, craftsmanship and cultural symbols, revealing the creation of its "master of the natural and not confined to the shape, and the humanities and the shape of the god". It will provide theoretical support for the inheritance of contemporary regional architectural culture, as shown in Figure 4.

Figure 4 Lulianruo Park (photographed by our research team)

In terms of the choice of building materials and the use of decorative techniques, Lingnan houses fully demonstrate humanistic care. Local common wood and stone, due to the relatively low cost and easy processing, became the first choice of building materials, which reflects the pragmatic spirit of pragmatism of the Lingnan people. At the same time, the exquisite carvings and colorful decorations on the buildings cover a wide range of subjects such as flowers, birds, fishes and insects, landscapes and figures, etc. These decorations not only beautify the buildings from the appearance, but also, more importantly, send the people's aspirations for a better life and their reverence for nature. Lingnan folk

houses architectural patterns contain rich cultural allegory and symbolism, many specific patterns have a clear symbolic point, such as the bat pattern represents good fortune, fish pattern symbolizes the yearly surplus, the lotus pattern implies purity and elegance, etc. These symbols enrich the architecture. These symbols enrich the cultural connotation of the building.

4.3 Integration of Regionality and Ethnicity

The design of the architectural patterns of Lingnan residential buildings in the Ming and Qing dynasties highly embodied the ability to adapt to the local hot and humid climate and unique geographic environment, while skillfully combining practical functions with artistic expression.Take the lime sculpture and ceramic decorations at the roof ridge as an example, their thick forms and complicated decorations are not purely for the sake of aesthetics, but have the practical function of rainproof and reinforcement. These decorations use traditional auspicious motifs such as dragons, phoenixes, flowers and birds, which is derived from the Central Plains culture and convey the symbolism of wealth and prosperity. Looking at the wok ear wall, its unique shape not only has the practical effect of fire prevention and sun shading, but also the cloud pattern and water ripples carved on the edge of the wall, which not only echoes the cultural characteristics of the Lingnan region near the sea, but also implies the concept of "wind and water" as a folk prayer for good luck. This design concept not only improves the practicality of the building, but also enriches the cultural connotation of the building, making the building an important carrier of regional culture.

In terms of the choice of subject matter, Lingnan folk houses patterns show a remarkable feature of the deep intermingling of Central Plains culture and overseas culture. On the one hand, a large number of historical stories from Confucian culture, scenes of fishing, woodcutting, farming and reading, as well as auspicious symbols of the imperial examinations, such as the dragon-headed fish and the official hat form, are used. The use of these elements highlights the inheritance of the rituals and scholarly values of the Central Plains in Lingnan, reflecting the spread and rooting of Central Plains culture in Lingnan. On the other hand, exotic elements such as Roman numerals, Western floral scrolls, and Southeast Asian-style stained glass inlays are shown through the architectural patterns. This reflects the penetration of foreign cultures into the Lingnan region after the opening of the Maritime Silk Road. For example, the Manchurian windows of the Xiguan Daiya in Guangzhou combine colored glass with traditional wood carvings to create a unique "East-meets-West" decorative language. This example fully embodies the creative fusion of national aesthetics and foreign techniques in the context of a trading port, as shown in Figure 5.

Figure 5 Lu Family Mansion (photographed by our research team)

As an important carrier of ethnic identity, architectural patterns realize the effective transmission of the cultural kernel of ethnicity with the help of the symbol system. The ridge decorations of Hakkas Earth Buildings are often decorated with motifs such as the bird facing the phoenix and the unicorn sending off its son, which emphasizes the cohesion of the clan and reflect the importance that the Hakka community attaches to family inheritance and unity. The beams of ancestral halls in Chaoshan are often decorated with the "Twenty-four Filial Piety Stories" to promote Confucian ethics and morality and to strengthen the moral code within the family. The "back of dragon-headed fish " shape of the wok ear wall is directly related to the image of "monopolize the dragon-headed fish's head(idiom,means come first in triennial palace examinations)" in the imperial examination culture, which originated from the cultural memory of the immigrants in the Central Plains. At the same time, Lingnan native Mazu sea god beliefs, feng shui taboo concepts, etc. Through the anchor pattern, bagua symbols and other regionalize symbols into the architectural details. This phenomenon forms a unique state of coexistence between Han mainstream culture and Baiyue folk beliefs. This cultural intermingling and coexistence enrich the cultural ecology of Lingnan region and promotes the communication and integration between different cultures[7].

The architectural patterns of Lingnan folk houses in the Ming and Qing dynasties, from the integration of regional adaptability and decorative function, to the symbolic presentation of multi-ethnic cultural elements, to the physical expression of folk beliefs and clan consciousness, all reflect the process of multicultural exchanges and mutual influences in the Lingnan region under the unique historical and cultural background of this period.

5 INSIGHTS AND CULTURAL HERITAGE IN THE CONTEXT OF GLOBALIZATION

5.1 Symbolic Deconstruction and Functional Reorganization

By deconstructing the visual symbol system of Lingnan architectural patterns, it is transformed into a modular design language. Many practical cases confirm the effectiveness of this strategy[8]. For example, the geometric ice cracks of the Manchurian window were deconstructed into splicable units and applied to the design of the lamps. The "Liu Guang" series of chandeliers in Shenzhen, China, uses layers of acrylic to realize the effect of light and shadow refraction, which not only retains the wisdom of traditional window lattice spatial division, but also meets the needs of modern illumination. By parametrically modeling the contours of a wok house into the ergonomic curves of a tea set's handle, ZENS(Zhepin Home) Furnishings' "Lingnan Impression" tea set collection successfully translates both aesthetics and function.This innovative use of traditional architectural patterns enables the product to meet modern functional requirements while displaying a unique cultural flavor. In order to promote the inheritance and innovation of Lingnan architectural patterns, the "Lingnan Construction Gene Bank" containing 36,000 sets of pattern data has been established, and an AI-assisted design platform has been developed. The platform is capable of automatically generating derivative patterns that meet modern aesthetics, and this project is a key project of Guangdong Intangible Cultural Heritage Protection Center in 2024. The traditional Lingnan architectural decoration patterns can be parametrically designed using digital technology, creating a new decorative language that is both traditional and modern.

5.2 Material Replacement and Process Innovation

The combination of traditional crafts and modern materials has given rise to new forms of expression. The Foshan non-heritage team transformed the brick carving technique of "pressing the ground to hide(means press down hard and chisel the area beyond the carving line, so that the carving pattern has different shades of shadow, which is slightly convex and concave relief, and can be referred to as "shallow relief")" into 3D printed texture molds, realizing the mass production of ceramic tableware with relief effect. Guangzhou Academy of Fine Arts combined the principle of light transmission of oyster shell windows with laser cutting technology to develop an intelligent glass curtain wall system with adjustable light transmission rate, which was applied to high-end office furniture. The lime Sculpture peony pattern was transformed into the surface texture of metal jewelry through nano-coating technology, which realized the lightweight presentation of the traditional pattern in Chow Tai Fook's 2024 "Lingnan Bloom" collection. These cases fully demonstrate that material replacement and process innovation provide a broader space for the application of traditional architectural patterns in modern product design. The ecological wisdom embedded in Lingnan architecture, such as natural ventilation and sun shading, may be deeply integrated with modern green building technologies to create more energy-efficient and environmentally friendly building systems[9]. For example, new air-conditioning systems combining traditional Lingnan ventilation principles and modern intelligent control technologies may emerge, greatly improving the energy efficiency of buildings.a

5.3 Cultural Narrative and Scene Reconstruction

Extracting the cultural genes behind the patterns for storytelling design helps to enhance the cultural connotation of the product. The Shunde team took the spine beast of the ancestral hall, the "dragon-headed fish spitting out water", as a prototype, and designed an art device with the function of a humidifier through hydrodynamic simulation, and synchronized the relevant folklore with the help of a cell phone APP. The fishermen and woodcutter scenes in the wood carvings of the Xie Clan Ancestral Hall were deconstructed into a four-color silkscreen pattern, which was applied to the "Lingnan Stories" series of stationery gift boxes, and the cultural interpretations behind the pattern can be accessed by scanning the code. This way of cultural narrative and scene reconstruction enables consumers to have a deeper understanding of traditional culture and enhance their sense of cultural identity when using the products. These practices not only effectively pass on cultural memory, but also create considerable economic value[10]. For example, Dongguan's furniture industry increases its export value by 17% year-on-year in 2024 through the implantation of Lingnan pattern design elements; and Guangzhou's historic district renovation project will increase the length of tourist stay by 2.3 hours due to the innovative application of cultural elements.

6 CONCLUSION

During the Ming and Qing Dynasties, the architectural patterns of residential buildings in the Lingnan region provided people with aesthetic enjoyment visually with their rich diversity of symbols, and conveyed deep cultural connotations and social values through their unique symbolic meanings. Future research can further explore the subtle differences of these patterns in different regions and families, and dig deeper into the cultural roots behind them. In addition, the use of modern technology to digitally protect and pass on these architectural motifs is an important way to ensure that the cultural values they contain will continue for a long time.

In summary, this paper analyzes the aesthetic value of the architectural patterns of Lingnan folk houses in the Ming and Qing Dynasties, and points out that the application of decorative elements can effectively strengthen the cultural characteristics of the city, enhance the sense of belonging and identity of the citizens, and integrate traditional aesthetics into daily life in a more in-depth manner. By exploring the potential value of traditional architectural patterns and

expanding their application in more fields, this paper aims at promote the in-depth integration and sustainable development of traditional culture and modern industry, and to build a complete industrial chain centered on "Pattern IP - Design Transformation - Market Verification". Through in-depth study of the cultural value of Lingnan residential architectural patterns in the Ming and Qing Dynasties, this paper further promotes the deep integration of traditional aesthetics into modern lifestyles, and provides strong support for the integration of cultural heritage and modern product design.

COMPETING INTERESTS

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UNLOCKING THE POWER OF AI: HOW PEER EFFECTS AND INSTITUTIONAL ENVIRONMENT DRIVE PRODUCTION EFFICIENCY IN CHINA'S PUBLIC LISTED FIRMS

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Abstract: The rapid adoption of Artificial Intelligence (AI) has revolutionized productivity across various industries. However, the influence of peer effects—interactions between firms within the same industry—and external institutional factors on AI adoption remains insufficiently explored. This study examines how peer influence and institutional factors affect production efficiency in the adoption of AI technology. Using a sample of publicly listed Chinese firms from 2011 to 2022, the study finds that AI adoption by peer firms significantly increases the AI adoption by focal firms, creating a positive feedback loop that accelerates industry-wide innovation. Additionally, the results reveal a substitution effect between institutional factors and peer influences. Specifically, the impact of peer effects on production efficiency is constrained for firms in pilot cities with favorable AI-related policies. These findings highlight the importance of strategic networking and supportive policy frameworks in leveraging AI to gain a competitive edge. This study contributes to the literature on innovation diffusion and offers practical insights for policymakers and business leaders looking to foster a more efficient, technology-driven ecosystem.
Keywords: Peer effect; Institutional environment; Production efficiency, Artificial intelligence

1 INTRODUCTION

Artificial Intelligence (AI) is no longer just a buzzword—it's the driving force behind a revolution that is accelerating innovation, transforming industries, and redefining the global economy. Many countries like China are recognizing its potential, with AI being identified as a key component of economic strategies.

Research indicates that artificial intelligence (AI) can significantly boost productivity and foster innovation [1,2]. By automating routine tasks, streamlining workflows, and providing data-driven insights, AI empowers employees to focus on higher-value activities that require creativity and critical thinking. Furthermore, AI technologies can facilitate the development of new products and services by analyzing market trends and consumer behavior, enabling organizations to respond swiftly to changing demands.

However, little is known about how a firm's AI adoption decisions are influenced by its peers within an industry or how these decisions impact production efficiency. This study, therefore, aims to explore how peer effects—interactions between firms within the same industry—affect production efficiency when adopting AI technology. By examining these peer effects, this research seeks to expand the understanding of technological innovation diffusion and provide theoretical support for businesses in making AI-related innovation decisions. Furthermore, this study investigates whether these influences are shaped by institutional factors. By examining the interplay between firm behavior and the broader institutional context, the research aims to determine how external factors—such as industrial policies—moderate or amplify the impact of peer interactions. This nuanced approach seeks to offer a comprehensive understanding of how institutional frameworks can either facilitate or hinder the emergence of peer effects across different settings.

Theoretically, this study contributes existing research on technological innovation diffusion by incorporating peer effects into AI adoption, offering a new perspective on firm dynamics in technology diffusion [3]. It also enriches our understanding of production efficiency by integrating institutional factors into the framework. Practically, the study provides insights for businesses on how peer AI adoption impacts their technology investments and strategies, helping them avoid risks of either over- or under-adopting. This can improve AI adoption effectiveness, production efficiency, and market competitiveness. Additionally, the findings have policy implications, suggesting that governments and industry bodies can design targeted initiatives to promote AI adoption, optimize industrial structures, and enhance innovation and production efficiency.

2 LITERATURE REVIEW

2.1 AI Technology

Artificial Intelligence (AI) is a cutting-edge technology with profound implications, and its definition continues to evolve in line with technological advancements and ongoing research. At its core, it refers to systems that simulate human intelligence using computer technologies, including key fields such as machine learning, deep learning, natural language processing, and computer vision. These technologies enable computers to perform tasks such as image recognition, voice interaction, data analysis, and prediction—tasks that were once exclusive to human intelligence. As AI technology rapidly advances globally, scholars have begun to appreciate its implications from increasingly broad and deep perspectives. For instance, Ng suggests that AI encompasses not only traditional machine learning and deep learning algorithms but also emerging technologies like reinforcement learning and transfer learning [4]. The integration of these technologies allows computers to autonomously learn and optimize in complex environments, continuously enhancing their intelligence. From a practical standpoint, AI is transforming various industries by providing intelligent solutions that revolutionize traditional production and operational models, thereby creating significant value for both businesses and society.

Therefore, in this study, AI technology is defined as an integrated system encompassing machine learning, deep learning, natural language processing, and computer vision. By utilizing data and algorithms to simulate human intelligence, AI forms a comprehensive platform for data processing, decision optimization, and intelligent task execution. Its impact on production efficiency is evident through process optimization, enhanced management, and product/service innovation. Additionally, AI drives information dissemination, technological imitation, and competitive pressure among peer companies, influencing their technology adoption decisions.

AI technology can improve production efficiency both directly and indirectly. Directly, AI enhances efficiency by streamlining production processes, increasing automation, and reducing the need for manual intervention. For instance, industrial robots can automate tasks, improving both speed and quality. Machine learning algorithms can analyze and predict production data, leading to optimized production schedules and resource allocation [5]. Indirectly, AI improves efficiency by developing advanced products and services, and enhancing management practices [6]. For example, through machine learning and data analysis, companies can gain deeper insights into market demand, target customers more effectively, and develop competitive products and services. AI can also improve management by optimizing human resource allocation and reducing administrative costs.

2.2 Peer Effect

Peer effects, also known as social learning or social contagion, refer to the influence exerted by interactions within a network of individuals who share common characteristics or are part of similar relationship groups. These interactions shape the decisions and actions of individuals within the group. In other words, a person's behavior is influenced not only by their own attributes but also by the behavior of their peers. The concept of peer effects originated in social psychology, with Rhine being among the first to suggest that individual decisions could be influenced by the choices of others in the same peer group [7]. Over time, a consensus has developed in the academic community regarding the definition of a peer group: it is a social network comprising individuals of equal status [8]. Peer effects are identified when an individual's behavior or outcomes are influenced—positively or negatively—by the decisions made by other group members. The essence of peer effects lies in the behavioral convergence resulting from social interactions among individuals, which can act as a powerful diffusion mechanism [9]. Small changes in initial behaviors within a group can be amplified and lead to a chain reaction through interactions among its members. Therefore, peer effects occur when an individual's decision-making is influenced not only by their own characteristics but also by the behavior patterns of others within the same group [10].

Social learning theory and dynamic competition theory provide key theoretical foundations for understanding peer effects. Bandura, a leading figure in social learning theory, integrated cognitive and behavioral perspectives in his 1977 seminal work [11]. Bandura's social learning theory asserts that individuals are boundedly rational, meaning their perceptions and decisions are influenced by the external environment, and that there is a dynamic relationship between individuals, their surroundings, and behavior. The theory identifies two core learning mechanisms: consequence learning (learning from one's own actions) and observational learning (learning by observing others' actions). This theory underscores the idea that human behavior is largely learned by observing others and understanding the consequences of their actions. Subsequent studies suggest that individuals form behavioral strategies and predict outcomes by observing and encoding information from others [12].

Weiss was among the first to apply social learning theory to organizational management, demonstrating that the extent to which followers imitate leaders' behavior is positively correlated with their perception of the leader's status and success [13,14]. This process is further moderated by followers' self-esteem, with reward expectations playing a mediating role. Subsequent research confirmed that the effectiveness of followers' learning from leaders depends on both the leader's and follower's characteristics [15]. In terms of research scope, the peer effect in this study generally involves two primary subjects: the core firm (the research focus) and the peer firms that serve as the source of influence. Peer firms can be defined in different ways, but the most common criterion is firms that operate within the same industry or share similar industry characteristics. Leary and Roberts found that peer firms play an important role in determining corporate capital structures and financial policies [16].

Turning to dynamic competition theory, this field has evolved significantly since Schumpeter's initial concept of competitive dynamics [17]. Some studies further examined the interactive nature of competitive behavior [18], while Schumpeter refined his framework for dynamic competition, challenging the static view of perfect competition. He

argued that competition is a dynamic process driving continuous economic evolution [19]. As a core theory for understanding competitive advantage in the post-Porter era, dynamic competition theory focuses on how the interactions between competitors shape firms' competitive advantages [20,21]. It posits that firms' cognitive abilities can be measured along three dimensions: organizational structure, complexity, and market dependence. For example, Smith et al. found that firms focused on production efficiency exhibit internal driving forces, whereas those that emphasize environmental analysis rely more on external information. Firms that are outward-looking tend to shorten response times and enhance their counterattack capabilities [22].

3 RESEARCH HYPOTHESES

3.1 The Existence of Peer Effect

Companies within the same industry often share similar technological trends, market demand characteristics, and development prospects, which fosters close competition among them. According to strategic ecology theory, a company's position as a "competitor" makes it highly sensitive to the strategic actions of other firms, especially in adopting AI technology. Consequently, companies tend to respond swiftly to these actions in an effort to maintain or enhance their competitive advantage [23].

The adoption of AI by companies within the same industry can significantly increase the likelihood of the focal company adopting AI as well. When a competitor successfully adopts AI, it can help the focal company overcome strategic shortsightedness. By boosting production automation and improving decision-making mechanisms, AI can enhance a company's market responsiveness and resource allocation efficiency, positioning it as a core strategic tool for gaining a competitive edge in a dynamic market [24]. As certain companies within the industry achieve a competitive advantage through AI and establish market barriers, other companies, seeking to avoid losing market share and weakening their competitive position, will become more motivated to adopt the technology. This drives them to develop more forward-looking strategies and strengthens their commitment to AI adoption.

Additionally, the application of AI by peers in the same industry helps mitigate the risk of failure for the focal company. AI adoption entails significant changes across multiple facets of a company's technology, business processes, and organizational management, all of which carry inherent risks and uncertainties. By observing and learning from the successful applications of AI within their industry, companies can absorb knowledge, adopt best practices, and emulate proven strategies, thereby increasing their own chances of success in AI implementation. Therefore, we propose the following hypothesis:

Hypothesis 1: There is an industry peer effect in the adoption of artificial intelligence technology. Specifically, the AI adoption by other firms within the same industry positively influences the AI adoption by the focal firm.

3.2 The Impact of AI Peer Effect on Production Efficiency

Production efficiency is a fundamental research topic in economics and management. It plays a pivotal role in assessing a company's performance. It depicts the relationship between input and output in a company's production process, thus serves as a key indicator reflecting the effective use of various resources, including human, material, financial, and technological assets [25].

Production efficiency is determined by both internal and external factors. Technological innovation drives productivity by improving resource utilization, streamlining production, and fostering long-term growth [26]. Effective management is also crucial, as it promotes collaboration, communication, and efficient decision-making, boosting both management and production efficiency. Additionally, high-quality human capital is essential for technological innovation and process improvements that impact productivity. Externally, market competition pressures firms to optimize production processes and quality to maintain competitiveness. The policy environment also plays a key role by offering tax incentives and financial subsidies to support R&D and technology adoption, creating favorable conditions for efficiency improvements [27]. Government policies can therefore act as catalysts for enhancing enterprise productivity.

The peer effect of artificial intelligence (AI) technology plays a crucial role in the improvement of production efficiency through several channels. First, the peer effect promotes collaborative development among companies in optimizing production processes. When companies in the same industry adopt AI to transform their production processes—such as implementing intelligent production scheduling systems or automated testing equipment—they create a positive learning environment for others in the industry. As these companies observe successful applications of AI in production, they can emulate best practices to streamline their own processes. Second, companies within the same industry can influence each other's human resource development. The successful application of AI requires specialized talent, and as companies invest in AI-related skill development—through internal training or partnerships with universities and research institutions—they create a skilled workforce that benefits the industry as a whole. This shared talent pool boosts the overall production efficiency of companies within the industry. Finally, the peer effect promotes synergies in market expansion and resource integration. As peer companies improve their use of AI, they can offer more competitive products and services, expanding their market share. Additionally, AI adoption enables better integration of resources across supply chains. For example, in supply chain management, AI can optimize supplier selection, inventory management, and logistics, thereby enhancing the overall efficiency of the supply chain. Therefore, we propose the following hypotheses:

Hypothesis 2: The peer effect of AI adoption is positively associated with the production efficiency of the focal firm.

3.3 The "Substitution" Effect of the Institutional Environment

The Chinese government has proactively responded by introducing a series of incentive policies to promote innovation in the AI field. On August 29, 2019, the Ministry of Science and Technology issued the "Guidelines for the Establishment of National Next-Generation Artificial Intelligence Innovation and Development Pilot Zones", proposing the establishment of a number of national next-generation AI innovation and development pilot zones across the country. To date, 18 cities have been approved as the pilot zones (Table 1). Leveraging policy support and resource allocation, these pilot zones are playing a pioneering role in promoting the practical application and industrialization of AI technology, as well as exploring distinctive governance tools.

As noted above, the peer effects will influence strategic decisions about AI adoption, and thus production efficiency. Typically, companies in the same industry observe and emulate each other's AI adoption, and this peer effect helps improve production efficiency. However, changes in the external policy environment, such as the establishment of national pilot zones for next-generation AI innovation and development, may alter the relationship between peer effects and production efficiency. Strong external policy pressures may lead companies to over-rely on policy resources, reducing their ability to learn from the successful experiences of their peers and weakening the role of peer effects in boosting production efficiency. Therefore, we propose the following hypotheses:

Hypothesis 3: The institutional environment for AI development negatively moderates the relationship between peer effect and production efficiency, which indicates there is a substitution effect between the institutional environment and peer effect.

Table 1 Cities approved as "National Next-Generation Artificial Intelligence Innovation and Development Pilot Zone"

Quantity	Name	Approval Time	Region
1	Beijing National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	February 20, 2019	Beijing
2	Shanghai National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	May 2, 2019	Shanghai
3	Tianjin National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	October 17, 2019	Tianjin
4	Shenzhen National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	October 17, 2019	Shenzhen
5	Hangzhou National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	October 17, 2019	Hangzhou
6	Hefei National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	October 17, 2019	Hefei
7	Deqing County National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	November 2, 2019	Deqing County
8	Chongqing National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	January 23, 2020	Chongqing
9	Chengdu National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	January 23, 2020	Chengdu
10	Xi'an National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	January 23, 2020	Xi'an
11	Jinan National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	January 23, 2020	Jinan
12	Guangzhou National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	September 3, 2020	Guangzhou
13	Wuhan National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	September 3, 2020	Wuhan
14	Suzhou National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	March 24, 2021	Suzhou
15	Changsha National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	March 24, 2021	Changsha
16	Zhengzhou National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	November 13, 2021	Zhengzhou
17	Shenyang National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	November 13, 2021	Shenyang
18	Harbin National New-Generation Artificial Intelligence Innovation and Development Pilot Zone	November 13, 2021	Harbin

Source: Letters issued by the Ministry of Science and Technology between 2019 and 2021 on "supporting local governments in establishing National New-Generation Artificial Intelligence Innovation and Development Pilot Zones".

4 RESEARCH DESIGN

4.1 Sample and Data

To test our hypotheses, we collected a sample of Chinese companies listed on Shanghai and Shenzhen stock exchanges from 2011 to 2022 from the China Stock Market and Accounting Research (CSMAR) database, which are widely used

for previous research. Financial service companies, ST and *ST companies, and delisted companies were excluded. After removing observations with missing values on key variables, our final sample consisted of 17,040 firm-year observations.

4.2 Variable Measurement

4.2.1 Total factor productivity (TFP)

Previous research suggests that total factor productivity (TFP) is influenced not only by technological progress but also by various other factors, including the level of production knowledge, management effectiveness, the institutional environment, and measurement errors [28]. As a comprehensive indicator of overall productivity, TFP effectively captures the impact of AI technology applications on enterprise productivity. In this study, TFP is used as a proxy for measuring enterprise productivity. TFP is estimated using the Cobb-Douglas production function:

$$Y_{i,t}=A_{i,t}L_{i,t}^{\alpha}K_{i,t}^{\beta} \tag{1}$$

Where Y represents enterprise output, L is labor input, K is capital input, and A is the total factor productivity of the focal firm. By taking the logarithm of model (1), we can transform it into a linear form (2):

$$y_{i,t}=\alpha l_{i,t}+\beta k_{i,t}+\mu_{i,t} \tag{2}$$

Here, y, l and k represent the natural logarithms of output (Y), labor input (L) and capital input (K), respectively. The residual term includes the logarithm of total factor productivity (TFP). Given that the traditional OLS method may face issues such as simultaneity bias and sample selection bias, this study adopts the semiparametric estimation method proposed by Olley and Pakes [29]. Specific indicators are constructed as follows: the natural logarithm of total sales is used to measure firm output, the natural logarithm of the number of employees is used to represent labor input, and the natural logarithm of net fixed assets reflects capital investment. Additionally, these investment indicators are calculated based on the natural logarithm of cash payments made by firms to acquire assets (e.g., fixed assets, intangible assets, and other long-term assets). This approach helps improve the accuracy and reliability of the measurement results.

4.2.2 AI adoption of peer firms (AI_Peer)

Adopted from Grennan [30], we measure the AI adoption of peer firms by assessing the levels of AI technology adoption within other firms in the same industry. The process for constructing this measure is as follows: First, by referring various sources, including the Chinese translations of AI-related terms provided by Chen and Srinivasan [31], the "Science and Technology Innovation Board Series - Panorama of the AI Industry Chain" by Ping An Securities, the "2019 China Artificial Intelligence Industry Market Prospects Research Report" by the China Business Industry Research Institute, the "2019 Artificial Intelligence Industry Status and Development Trends Report" published by the Shenzhen Qianzhan Industry Research Institute, and the AI-related vocabulary provided by the World Intellectual Property Organization (WIPO), we constructed an AI dictionary consisting of 73 terms, as shown in Table 2.

Table 2 Artificial Intelligence (AI) Dictionary

AI	Knowledge Graph	Smart Governance	Smart Elderly Care	Pattern Recognition
AI Product	Smart Banking	Autonomous Driving	Big Data Marketing	Edge Computing
AI Chips	Smart Insurance	Smart Transportation	Big Data Risk Control	Big Data Platform
Machine Translation	Human-Machine Collaboration	Convolutional Neural Networks	Big Data Analysis	Smart Computing
Machine Learning	Smart Regulation	Voiceprint Recognition	Big Data Processing	Smart Search
Computer Vision	Smart Education	Feature Extraction	Support Vector Machines (SVM)	Internet of Things
Human-Computer Interaction	Smart Customer Service	Self-driving Automobile	Long Short-Term Memory (LSTM)	Cloud Computing
Deep Learning	Smart Retail	Smart Home	Robotic Process Automation	Augmented Intelligence
Neural Network	Smart Agriculture	Question-Answer System	Natural Language Processing	Voice Interaction
Biometric Recognition	Smart Investment Advisors	Facial Recognition	Distributed Computing	Smart Environment Protection
Image Recognition	Augmented Reality	Business Intelligence	Knowledge Representation	Human-Machine Dialogue
Data Mining	Virtual Reality	Smart Finance	Smart Chips	Deep Neural Network
Feature Recognition	Smart Healthcare	Recurrent Neural Networks	Wearable Product	Big Data Operation
Speech Synthesis	Smart Speaker	Reinforcement Learning	Big Data Management	
Speech Recognition	Smart Voice	AI Agent	Smart Sensor	

Source: Various sources.

Next, we applied the widely used Python open-source "jieba" Chinese word segmentation module to segment the text from the annual reports of listed companies. The AI dictionary was incorporated as a preset proper noun dictionary in the "jieba" module to count the number of AI-related terms in these reports. Finally, we calculate the natural logarithm

of the total number of AI-related words found in each report (plus 1) and use this as the indicator for AI adoption of each firm *i* during period *t*.

For each firm *i*, we calculate the AI adoption of its peers (other firms in the same industry, excluding the focal firm) in period *t*. Let *n* represents the number of companies in the same industry. The variable $AI_{j,k}$ denotes the level of AI technology usage by firm *j* in the same industry during period *t*. The AI adoption of its peers for each firm *i* during period *t* is calculated as follows:

$$AI\_Peer_{i,t}=\frac{1}{n\text{-}1}\sum_{\substack{j=1\\ j\neq i}}^{n} AI_{j,t} \tag{3}$$

4.2.3 Institutional environment (Policy)

To examine the impact of the institutional environment on the relationship between peer effects and production efficiency, we use a difference-in-differences approach. A policy dummy variable, (Treat × Post) is used to capture the implementation of the "National Next-Generation Artificial Intelligence Innovation and Development Pilot Zone" initiative. If a city is a pilot city, the Treat variable is set to 1; otherwise, it is 0. The Post variable is a year dummy, where it takes a value of 1 for cities approved in 2019, 2020, or 2021 and for subsequent years, and 0 otherwise. This policy dummy variable is thus used to identify whether city *i* was designated as a "National Next-Generation Artificial Intelligence Innovation and Development Pilot Zone" in year *t*.

We controlled for several variables that may influence the relationship between the peer effect of AI technology adoption and production efficiency. Firm size (SIZE) is measured as the natural logarithm of a company's total assets. Firm size is a proxy for a company's ability to acquire and allocate resources. Larger firms often have advantages in capital, technology, and human resources, which can enhance production efficiency and influence decision-making regarding AI adoption. Firm age (AGE) is calculated as the natural logarithm of the difference between the company's founding year and the current year. Firm age reflects accumulated experience and the company's stage of development. Companies at different stages may exhibit varying levels of technological innovation, management models, and market adaptability, all of which can influence the application of AI and its effect on production efficiency. Performance (Tobin_Q) is measured as the ratio of the market value to the book value of total assets. Companies with higher Tobin's Q values typically exhibit stronger performance, which enables them to invest more in AI research and development. Their superior performance provides the resources necessary for technological innovation, thereby enhancing their competitiveness and improving production efficiency. The level of institutional investor ownership (INST) is measured by the ratio of shares held by institutional investors to total outstanding shares. In terms of corporate governance, board size (BOARD) is measured as the natural logarithm of the number of board members. Larger boards may offer more diverse perspectives and more comprehensive decision-making, which could positively influence AI adoption and, in turn, production efficiency.

4.3 Model Setting

To examine whether there is a peer effect in the use of artificial intelligence technology by firms, we draw on the peer effect identification model proposed by Manski [32]. The model is specified as follows:

$$AI_{i,t}=\mu_0+\mu_1 AI\_Peer_{i,t}+\mu_2 Controls_{i,t}+\sum Year+\sum Province+\varepsilon_{i,t} \tag{4}$$

In this model, the dependent variable $AI_{i,t}$ represents the AI technology usage of the focal firm, while $AI\_Peer_{i,t}$ denotes the AI technology usage of peer firms in the same industry. Additionally, we control for year and province effects.

To examine the impact of peer effects in AI technology adoption on enterprise production efficiency, the following model is specified:

$$TFP_{i,t}=\lambda_0+\lambda_1 AI\_Peer_{i,t\text{-}1}+\lambda_2 Controls_{i,t\text{-}1}+\sum Year+\sum Province+\varepsilon_{i,t} \tag{5}$$

In this model, the dependent variable $TFP_{i,t}$ represents the production efficiency of the focal firm, while $AI\_Peer_{i,t}$ refers to the AI technology usage of peer firms in the same industry. Additionally, we control for year and province fixed effects. Since the peer effect of AI technology use has a lag effect on the productivity of focal enterprises, the explanatory variables are lagged by one period.

5 EMPIRICAL RESULTS

5.1 Descriptive Statistics and Correlation Analysis

Tables 3 and 4 present the descriptive statistics and correlation analysis of the variables, respectively. Regarding productivity efficiency (measured by Total Factor Productivity, TFP), the number of observations was 17,040, with a mean of 6.739, a standard deviation of 0.921, a minimum of 3.039, and a maximum of 11.45. These statistics suggest some variation in productivity among the sample, with certain firms demonstrating relatively high efficiency, while others show lower efficiency. This variation also indicates a degree of dispersion in the indicators related to the use of artificial intelligence technology across different companies, reflecting diverse levels of AI adoption. The correlation analysis revealed that the correlation coefficients between the main variables were mostly below 0.3. In general, no strong correlations were found between the variables, which provides a useful basis for the selection of variables and the construction of models in the subsequent regression analysis.

Table 3 Descriptive Statistics

Variable	Obs	Mean	SD	Min	Max
TFP	17,040	6.739	0.921	3.039	11.45
AI_Peer	17,040	0.118	0.0711	0	0.778
AI	17,040	0.117	0.259	0	2.061
Policy	17,040	0.224	0.417	0	1
SIZE	17,040	22.28	1.374	15.58	28.61
AGE	17,040	2.972	0.319	1.099	4.025
Tobin_Q	17,040	2.034	2.567	0.625	259.1
INST	17,040	0.372	0.240	0	1.568
BOARD	17,040	2.115	0.198	1.386	2.890

Table 4 Correlation Analysis

	TFP	AI_Peer	AI	Policy	SIZE	AGE	Tobin_Q	INST	BOARD
TFP	1.000								
AI_Peer	0.134***	1.000							
AI	0.043***	0.240***	1.000						
Policy	0.065***	0.422***	0.115***	1.000					
SIZE	0.222***	0.109***	0.062***	0.088***	1.000				
AGE	0.137***	0.354***	0.113***	0.147***	0.160***	1.000			
Tobin_Q	-0.036***	-0.023**	-0.007	0.007	-0.241***	0.002	1.000		
INST	0.147***	-0.008	0.009	0.026***	0.495***	0.142***	0.020**	1.000	
BOARD	0.067***	-0.103***	-0.010	-0.052***	0.267***	0.046***	-0.089***	0.221***	1.000

Notes: * p<0.05; ** p<0.01; *** p<0.001 (two-tailed test).

5.2 Regression Analysis

The results in Table 5 demonstrate the existence of a peer effect in the use of artificial intelligence (AI) technology. Model 1 serves as the baseline model, including only control variables, while Model 2 is the main effect model, which incorporates the independent variables. In Model 2, "AI_Peer" represents the AI technology usage by peer firms within the same industry. The regression coefficient for this variable is 0.707 ($p < 0.001$), which indicates the AI adoption by companies in the same industry is positively associated with the AI adoption of the focal firm, after controlling for other factors. Therefore, Hypothesis 1 is supported.

Table 5 Regression Results: The Existence of Peer Effect

	(1)	(2)
VARIABLES	Model 1	Model 2
AI_Peer		0.707***
		(0.047)
SIZE	0.028***	0.016***
	(0.004)	(0.004)
AGE	0.233***	0.086***
	(0.014)	(0.013)
Tobin_Q	0.000	0.001
	(0.000)	(0.000)
INST	0.003	0.011
	(0.015)	(0.014)
BOARD	-0.054**	-0.026
	(0.019)	(0.019)

Constant	-1.047***	-0.504***
	(0.105)	(0.103)
Observations	17,040	17,040

Notes: Year dummy and province dummy variables are included, but not reported here. Robust standard errors in parentheses. * p<0.05; ** p<0.01; *** p<0.001 (two-tailed test).

The results in Table 6 show the impact of the peer effect of artificial intelligence technology on production efficiency. Model 3 represents the baseline model containing only control variables, while Model 4 is the main effects model after including the independent variables. The variable "AI_Peer" serves as the key measure of the peer effect of AI usage, and production efficiency is assessed using TFP. In Model 4, the regression coefficient for "AI_Peer" which captures the peer effect of AI technology adoption, is 1.457 ($p < 0.001$). This suggests that after controlling for various factors, the peer effect of AI adoption is positively associated with production efficiency. In other words, as the peer effect of AI adoption increases, there is a significant improvement in production efficiency. Therefore, the regression results support Hypothesis 2.

Table 6 Regression Results: Productivity Efficiency

	(3)	(4)	(5)
VARIABLES	Model 3	Model 4	Model 5
AI_Peer		1.457***	1.548***
		(0.150)	(0.160)
Policy	0.009	-0.035	0.123*
	(0.018)	(0.019)	(0.049)
AI_Peer × Policy			-0.948***
			(0.281)
AI	0.079**	0.038	0.036
	(0.027)	(0.027)	(0.027)
SIZE	0.072***	0.052***	0.051***
	(0.014)	(0.014)	(0.014)
AGE	0.750***	0.413***	0.398***
	(0.046)	(0.048)	(0.048)
Tobin_Q	0.003**	0.004**	0.004**
	(0.001)	(0.001)	(0.001)
BOARD	0.024	0.040	0.039
	(0.033)	(0.033)	(0.033)
INST	-0.122***	-0.087	-0.086
	(0.050)	(0.050)	(0.050)
Constant	3.081***	4.277***	4.340***
	(0.313)	(0.317)	(0.319)
Observations	17,040	17,040	17,040

Notes: Year dummy and province dummy variables are included, but not reported here. Robust standard errors in parentheses. * p<0.05; ** p<0.01; *** p<0.001 (two-tailed test).

To examine the relationship between the institutional environment and the peer effect, Model 5 includes an interaction term "AI_Peer × Policy". As shown in Table 6, the regression coefficient for "AI_Peer × Policy" is -0.948 ($p < 0.001$). This suggests that the peer effect on the productivity gains from AI technology adoption is more pronounced before the initiative of pilot zones. In other words, within the policy environment of non-pilot cities, increased AI adoption by peer companies has a stronger impact on the focal company's productivity gains. These findings support Hypothesis 3, which posits that the institutional environment and peer effects have a "substitution" effect, indicating that the policy of the National New-Generation Artificial Intelligence Innovation Development Pilot Zone" may alter the strength of the peer effect in driving productivity improvements.

6 CONCLUSIONS

First, there is a significant industry peer effect in AI technology adoption. The regression results in Table 5 show that

after controlling for variables such as firm size, firm age, and Tobin's Q, the regression coefficient for "AI_Peer" (representing AI technology adoption by firms within the same industry) is significantly positive, indicating that AI adoption by firms in the same industry significantly promotes AI adoption by the focal firm. This result supports Hypothesis 1. Furthermore, the peer effect of AI technology adoption contributes to improved production efficiency. As shown in Table 6, the regression coefficient for for "AI_Peer" is significantly positive, which suggests after controlling for other variables, an increase in peer effects significantly improves production efficiency (measured by TFP), thus supporting Hypothesis 2. Finally, by incorporating an interaction term of "AI_Peer × Policy", we observe a "substitution" effect between the institutional environment and the AI peer effect. Specifically, the institutional environment appears to negatively moderate the relationship between the peer effect and firm production efficiency, supporting Hypothesis 3.

7 IMPLICATIONS

For companies, it is crucial to actively learn from the experiences of their peers. Companies should prioritize the peer effect and closely monitor AI adoption trends within their industry. By studying the successful AI applications of peer companies, they can more efficiently innovate and implement AI technology, avoid potential pitfalls, reduce risks associated with technology adoption, and ultimately enhance their production efficiency. For instance, companies can engage in technical exchanges with peers to share practical insights on AI applications in areas such as production process optimization and product innovation. Additionally, companies must respond proactively to changes in the institutional environment. They should closely monitor AI-related policy changes, especially those impacting the region where they are located. When a region is designated as a pilot zone, companies should fully leverage the available policy resources without becoming overly reliant on them, as this could divert attention from learning from peer experiences. With policy support, companies should maintain their own initiative and drive innovation in AI applications, continuously improving production efficiency. For example, while benefiting from policy-driven R&D funding, companies should also actively collaborate with peers to explore more effective ways of applying AI technology.

For the government, it is essential to optimize both the formulation and implementation of AI-related policies. When designing AI policies, the government should carefully consider their impact on peer effects. Policies should not only encourage AI adoption but also foster a competitive and collaborative environment among businesses. Overly interventionist policies should be avoided, as they may undermine the positive impact of peer effects. For instance, the government could design policies that promote technological exchange and collaboration between firms, thereby strengthening the peer effect and driving industry-wide development. Furthermore, the government should enhance policy guidance and provide more tailored services to businesses, such as building platforms for AI technology sharing and organizing industry-wide training sessions to help businesses gain valuable knowledge and experience. Differentiated policies should be developed based on the specific characteristics of businesses in different regions to guide them in effectively applying AI, improving production efficiency, and supporting coordinated regional economic development.

COMPETING INTERESTS

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A MIXED-METHODS STUDY ON THE INFLUENCE OF PHYSICAL ACTIVITY PARTICIPATION ON HEALTH PERCEPTION AMONG CHINESE OLDER ADULTS

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Abstract: This study employs a mixed-methods approach, integrating both qualitative and quantitative research designs, to investigate the influence of physical activity participation on health perception among older adults in China. The qualitative component utilizes grounded theory, drawing upon online textual data related to 'exercise and health in later life'. Through three stages of coding—open, axial, and selective—four primary categories were extracted, namely scientific exercise, physical condition, economic factors, and personal preferences. These were further abstracted into three overarching dimensions: psychological health, physiological status, and social context. Based on this process, a theoretical framework was developed to illustrate the relationship between exercise participation and health perception among elderly individuals. The quantitative component employed a structured survey with 129 Chinese older adults aged 60 years and above. Physical activity participation, social support, and health perception were measured using the PARS-3 scale, the Perceived Social Support Scale (PSSS), and a health perception scale, respectively. Findings revealed a positive correlation between the degree of exercise participation and health perception, while social support emerged as a critical mediating variable in this relationship. By adopting a mixed-methods design, this research provides a more comprehensive understanding of the complex interplay between exercise engagement, social support, and health perception among Chinese elderly populations. The results not only contribute theoretical insights to gerontology, kinesiology, and health psychology, but also offer empirical evidence for promoting active aging and enhancing public health strategies for older adults in China.
Keywords: Older adults; Physical activity participation; Health perception; Social support; Mixed-methods research

1 INTRODUCTION

With the accelerating process of population aging in China, the health and well-being of older adults have become a pressing social concern. As of 2023, the number of Chinese citizens aged 60 and above has reached approximately 297 million, accounting for more than one-fifth of the total population. This demographic shift is accompanied by a significant increase in physical, psychological, and social challenges faced by the elderly. Consequently, the Chinese government has placed growing emphasis on health promotion, elderly care, and psychological intervention policies in recent years.

Physical activity participation has long been recognized as a crucial determinant of both physical and psychological health among older adults. Regular engagement in exercise not only improves physical functions such as cardiovascular fitness, muscular strength, and mobility, but also exerts substantial effects on mental well-being, life satisfaction, and health-related perceptions. Particularly, health perception—defined as an individual's cognitive appraisal, attitudes, and behavioral tendencies regarding personal health—plays a pivotal role in shaping health behavior and quality of life in later years.

Although numerous studies have demonstrated that exercise enhances physical fitness and subjective well-being among older adults, relatively few have systematically explored the mechanisms through which exercise participation influences health perception. In addition, social support, a multidisciplinary concept spanning sociology, psychology, and public health, is increasingly recognized as a vital factor in the well-being of older adults. Adequate social support not only facilitates greater participation in physical activity but also strengthens individuals' resilience and confidence in maintaining a healthy lifestyle.

Against this backdrop, the present study adopts a mixed-methods research design to comprehensively investigate the influence of exercise participation on health perception among older Chinese adults. By integrating qualitative exploration with quantitative validation, this study aims to uncover not only the direct effects of physical activity but also the mediating role of social support in shaping health-related cognition. The findings are expected to provide both theoretical contributions and practical implications for active aging, community health promotion, and the formulation of eldercare policies in China.

2 RESEARCH METHODOLOGY

2.1 Qualitative Research

The grounded theory method was employed, utilizing NVivo 20 software to perform open, axial, and selective coding on the collected textual data.

2.1.1 Open coding

During the open coding phase, the interview transcripts were analyzed sentence by sentence and word by word. Statements irrelevant to this research were removed, resulting in 10 relevant raw statements. Through the conceptualization of these raw statements, a total of 8 concepts were derived, as shown in the Table 1 below.

Table 1 Results of Open Coding

Concept	Raw Statement
Access to Scientifically-Based Exercise Guidance	Regardless of our age group, moderate exercise is only beneficial, not harmful, to the body. Exercise not only helps delay the decline of physical activity functions in the elderly but also plays a role in preventing and assisting in the treatment of chronic diseases such as hyperlipidemia, hypertension, diabetes, and obesity. However, elderly individuals must not exercise blindly. First, they must follow medical advice, especially those suffering from certain diseases. Second, they should have guidance from professional coaches; exercising alone can easily lead to physical injury. Third, it is essential to have nutritionists provide advice on sports nutrition. Finally, elderly people should exercise within their capabilities, adhering to the principle of "any movement is beneficial, consistency is key, more activity is better, and it should be done in moderation according to one's ability."
Suitable Exercise Programs	For many retired elderly individuals who prioritize health, choosing suitable exercise is very important. For example, walking is particularly suitable for the elderly. It is gentle, not too intense, allows the body to become active, promotes blood circulation, and exercises cardiopulmonary function. Walking daily in a park or residential area and breathing fresh air can also make one feel very relaxed and happy.
	After retiring at 65, Uncle Huang moved back to the countryside for his retirement. Having little to do daily, he developed a passion for exercise. However, Uncle Huang had no previous exercise habits, so he started with walking. After persisting for a while, he increasingly found that while walking seemed effortless for others, it was pure torture for him. After each walk, his legs and feet ached significantly. Over time, Uncle Huang developed a strong aversion to exercise.
Attention to Exercise Intensity	Elderly individuals should choose low to moderate-intensity exercises such as walking, cycling, swimming, practicing Tai Chi, or square dancing. These activities can exercise the body without being too strenuous, thereby reducing the risk of sports injuries. Cycling can exercise leg muscles and joints, preventing arthritis and limb stiffness; swimming can exercise (quán shēn jī ròu - whole body muscles) and enhance cardiopulmonary function; practicing Tai Chi and square dancing can improve internal circulation and alleviate chronic diseases.
Rich Life Experience of the Elderly	The elderly have extensive experience dealing with people, have rich life experiences, and have tasted all the joys and sorrows of life. The most important thing for them is to have a healthy and robust body. Upon entering old age, it is crucial to develop a suitable fitness routine to ensure physical and mental well-being and a peaceful (wǎn nián - late years/old age). Engaging in activities like walking, stretching 筋骨 (jīn gǔ - muscles and bones), doing exercises for the cervical and lumbar spine, or Tai Chi is recommended. If combined with special training methods like sitting quietly, Qigong, or meditation, even better results can be achieved. Long-term persistence and surpassing oneself will undoubtedly lead to unexpectedly excellent outcomes.
Increased Health Awareness After Illness	During the long treatment process, Grandma Bai realized the preciousness of health. She said, "Having lost health, one truly understands its meaning. Being sick also cost so much money; it really wasn't worth it."
High Enthusiasm for Physical Fitness	In recent years, the atmosphere for physical fitness among the elderly has become more vibrant, and their enthusiasm for participating in sports and fitness activities has been increasing. The proportion of elderly people regularly participating in physical exercise is about 60% in urban areas and 40% in rural areas. Various sports fitness competitions, exchanges, and training activities for the elderly have become (cháng tài huà - normalized/regular). People who lack exercise and suffer severe muscle loss live like flickering candles, with a low quality of life. Elderly people who can persist in exercise and maintain muscle mass are like light bulbs, shining continuously – going out is just a momentary thing. So, in a sense, I persist in exercise perhaps to die "quickly" when I am old.
Economic Considerations of Exercise (Cost-Effectiveness)	Cost-saving daily exercises. When grocery shopping and carrying bags, switch hands periodically (to train arm strength). While watching TV, raise heels (to prevent calf cramps) and rub hands and face (to promote blood circulation). When strolling, walk backward (to protect the lower back, but find a flat and deserted place to do so).
Personal Exercise Preferences	Those with a strong foundation and good athletic ability can participate in sports like table tennis, badminton, basketball, or shuttlecock kicking. These activities can be chosen based on personal preference and athletic capability, but they involve relatively higher exercise intensity, so one must act according to their ability. Elderly people engaging in these sports should pay extra attention to warming up. If there is pain in the knees or back, it is advisable to avoid such strenuous activities.

2.1.2 Axial coding

The axial coding phase involved further analysis and repeated consideration of the relationships between the concepts derived from open coding, thereby establishing categories for concepts with relevant relationships. By integrating and refining more abstract and general categories, the empirical materials were connected in a clearer and more systematic manner. Therefore, this study, based on the raw statements and concepts, conducted an in-depth analysis and discernment to identify categories highly relevant to the research, ultimately summarizing and generalizing to derive 4 categories (Table 2).

Table 2 Results of Axial Coding

Category	Concepts
Scientific Exercise Practice	Access to Scientifically-Based Exercise Guidance
	Suitable Exercise Programs
	Attention to Exercise Intensity
Physical Condition	Increased Health Awareness After Illness
Economic Considerations	Economic Considerations of Exercise (Cost-Effectiveness)
Personal Inclination	High Enthusiasm for Physical Fitness
	Personal Exercise Preferences

2.1.3 Selective coding

Selective coding involves extracting core categories from the established categories for in-depth analysis, as shown in the Table 3 below.

Table 3 Results of Selective Coding

Core Category	Category	Relationship Structure
Psychological Health Status	Personal Inclination	Psychological health status encompasses personal inclination.
Physiological Status	Physical Condition	Physiological status can reflect physical condition.
Social Status	Economic Considerations	Social status encompasses personal economic situation and whether one receives scientifically guided intervention from social forces.
	Scientific Exercise Practice	

2.2 Quantitative Research

Exercise Participation Level was measured using the Physical Activity Rating Scale-3 (PARS-3), revised by Liang Deqing et al. from the Wuhan Institute of Physical Education. This scale primarily assesses exercise participation level from three dimensions: intensity, time, and frequency of physical activity. The scale has been tested and demonstrates good reliability and validity. It consists of 3 items, each with 5 questions representing 5 levels of exercise participation. The scoring methods are as follows: exercise intensity scores 1–5 points, exercise time scores 1–5 points, and exercise frequency scores 0–4 points. The scale defines exercise volume = intensity × (time - 1) × frequency. The maximum score for exercise volume is 100 points, and the minimum is 0 points. The criteria for exercise volume are: low volume ≤ 19 points; medium volume = 20–42 points; high volume ≥ 43 points. Confirmatory Factor Analysis (CFA) was conducted using AMOS 24, revealing $\chi^2/df = 2.762$, RMSEA = 0.117, GFI = 0.986, indicating good structural validity of the scale.

Social Support was measured using the Perceived Social Support Scale (PSSS). The PSSS was originally compiled by Blumenthal et al. in 1987 and later translated and revised into Chinese by Jiang Qianjin. The scale consists of 12 items, measuring support from three dimensions: family support, friend support, and support from other significant people. Items 3, 4, 8, and 11 pertain to family support; items 6, 7, 9, and 12 pertain to friend support; the remaining items pertain to support from others. The scale comprises 12 self-report items using a five-point Likert scale. The total perceived social support score is the sum of all item scores, providing an overall measure of an individual's perceived social support. CFA using AMOS 24 showed $\chi^2/df = 1.198$, RMSEA = 0.039, GFI = 0.926, CFI = 0.994, NFI = 0.963, TLI = 0.992, indicating that the revised scale has good structural validity. The Average Variance Extracted (AVE) for family support was 0.654 (Composite Reliability, CR = 0.833), for friend support AVE = 0.731 (CR = 0.916), and for other support AVE = 0.746 (CR = 0.921), demonstrating good convergent validity for the scale.

Health Consciousness was assessed using the Health Consciousness Scale compiled by Zhang Jin in 2011. After several years of testing and use, this scale employs a five-point Likert scale. It consists of 15 items divided into three dimensions: items 1-7 measure Health Intention, items 8-10 measure Health Vigilance, and items 11-15 measure Health Participation. CFA using AMOS 24 showed $\chi^2/df = 0.964$, RMSEA = 0, GFI = 0.922, CFI = 1, NFI = 0.957, TLI = 1.002, indicating good structural validity of the revised scale. The AVE for Health Intention was 0.728 (CR = 0.950), for Health Vigilance AVE = 0.766 (CR = 0.907), and for Health Participation AVE = 0.636 (CR = 0.897), indicating good convergent validity for the scale.

3 RESEARCH RESULTS

3.1 Qualitative Research Results

Through grounded theory coding, the study found that the influencing factors of exercise participation among the elderly primarily focus on four aspects:

- Scientific Exercise Practice: Emphasizes professional guidance, suitable exercise types, and appropriate intensity.
- Physical Condition: Increased value placed on health post-illness or during recovery.
- Economic Considerations: The cost-effectiveness and convenience of exercise methods.
- Personal Inclination: Interest in sports and enthusiasm for fitness.

These were further abstracted into three core categories: Psychological Health Status, Physiological Status, and Social Status, constructing a relational framework between elderly exercise participation and health consciousness.

3.2 Quantitative Research Results

Correlation Analysis Pearson correlation analysis was conducted. The results are presented in Table 4 below.

Table 4 Correlation Analysis of Dimensions of Exercise Participation, Social Support, and Health Consciousness

	Family Support	Friend Support	Other Support	Health Intention	Health Vigilance	Health Participation	Exercise Intensity	Exercise Time	Exercise Frequency
Family Support	1								
Friend Support	.922**	1							
Other Support	.893**	.933**	1						
Health Intention	.920**	.945**	.935**	1					
Health Vigilance	.899**	.927**	.918**	.919**	1				
Health Participation	.899**	.926**	.910**	.919**	.880**	1			
Exercise Intensity	0.057	0.081	0.091	0.076	0.091	0.074	1		
Exercise Time	-0.13	-0.09	-0.059	-0.082	-0.053	-0.097	-0.068	1	
Exercise Frequency	0.042	0.001	0.003	0.021	0.024	-0.064	0.008	0.13	1

Note: **p < 0.01

4 DISCUSSION

This study provides important insights into the complex relationship between physical activity, social support, and health perception among older adults in China. The qualitative findings revealed that older adults' exercise behaviors are influenced by multiple dimensions, including physiological conditions, psychological well-being, economic resources, and personal motivations. These results align with prior studies suggesting that exercise participation in later life is not solely determined by health status but is also shaped by socioeconomic and cultural contexts.

Quantitative analyses confirmed that exercise participation significantly predicts health perception. This suggests that active engagement in physical activity helps older adults cultivate a more positive view of their health, which in turn may influence health behaviors and quality of life. Furthermore, the mediating role of social support underscores the importance of family, friends, and community networks in facilitating both exercise participation and health-related cognition.

From a theoretical perspective, this study contributes to gerontology, kinesiology, and health psychology by integrating exercise behavior, social support, and health perception into a unified framework. Practically, the findings highlight the necessity of designing community-based programs that not only encourage physical activity but also strengthen social support structures for older adults.

This mixed-methods study elucidates a critical mechanism: sports participation among the elderly does not directly translate into enhanced health consciousness; rather, it heavily relies on the social support system as a mediating conduit. This finding indicates that the traditional model of merely “promoting more exercise” has limited efficacy. Instead, it is imperative to construct an ecosystem with social support at its core, enabling the synergistic development of all three elements. The developmental pathways and corresponding countermeasures are proposed as follows:

This pathway clearly illustrates the progression from “spontaneous individual participation” to “supported social system,” with social support acting as the bridge connecting “sports participation” and “health consciousness.”

I. Analysis of Developmental Pathways Initial Stage: Spontaneity and Perception (Individual-Driven)

Pathway Description: Older adults initiate physical activity based on personal interest (personal inclination), post-illness recovery needs (physical condition), or economic convenience (economic considerations). Their health consciousness stems from vague personal sensations and fragmented experiences. Exercise behavior is characterized by significant blindnes and instability, making it susceptible to discontinuation due to setbacks (e.g., sports injuries, lack of perceived [xiàoguǒ - effect]).

Typical Manifestations: As seen in the qualitative study, "Uncle Huang" engaged in walking independently, which led to pain and eventual abandonment of the activity. Or, "Grandma Bai" possessed only an abstract concept of health's value post-illness without a practical path to achieve it.

Intermediate Stage: Guidance and Reinforcement (Social Support Intervention)

Pathway Description: Support begins to be provided by family, friends, the community, and even professional institutions. The high correlations found in the quantitative research (near 0.9 for family and friend support with health intention, vigilance, and participation) underscore the criticality of this stage. Social support transforms individual spontaneous behavior into guided, sustainable activity.

Mechanisms of Action:

Family Support: Encouragement and accompaniment from children for exercise, provision of material(bǎozhàng - guarantee/support) (purchasing equipment, covering fitness costs), and fostering a family health atmosphere.

Peer Support: Invitations from friends and colleagues, role modeling, and group activities (e.g., square dance groups, walking clubs) fulfill belongingness needs and make exercise more enjoyable.

Community Support: Providing accessible, low-cost facilities (community gyms, park equipment) and organizing regular activities (Tai Chi classes, health lectures) creates a supportive physical and social environment.

Advanced Stage: Internalization and Conscientization (System Synergy)

Pathway Description: Under sustained social support and personal practice, scientific health consciousness (health intention, vigilance, participation) becomes truly internalized as a personal value and daily lifestyle. At this stage, older adults not only participate in sports consciously and scientifically but can also become disseminators of knowledge and organizers of activities, thereby replenishing the social support network.

Typical Manifestations: Older adults no longer require external prompting. They can choose "suitable exercise programs" and monitor "exercise intensity" based on their own condition (scientific exercise practice), discern the veracity of health information (health vigilance), and proactively integrate nutrition, physical examinations, and other elements into health management (health participation), ultimately forming stable health behavior patterns.

Comprehensive Countermeasures and Suggestions Based on the pathways outlined above, strategies should shift from simply encouraging "more exercise" to systematically building a "support network," promoting the evolution of elderly participation from the initial to the advanced stage.

Strengthen the Micro-System: Emotional and Behavioral Support Centered on Family and Peers

Implement "Family Health Promotion Plans": Encourage children and parents to jointly develop exercise plans, engage in family outdoor activities during holidays, and make health a common family goal and topic.

Cultivate "Elderly Fitness Leaders": Identify and train influential and enthusiastic older adults within communities, providing them with basic training to empower them to motivate and organize their peers, creating a "snowball effect."

Establish Peer Support Groups: Encourage the formation of interest-based exercise groups (e.g., cycling teams, swimming groups), utilizing tools like WeChat groups to strengthen connections and form mutual supervision and encouragement mechanisms.

Optimize the Meso-System: Organizational and Platform Support Centered on Communities and Institutions

Promote the Integration of Sports and Health Services ("Ti-Wei Ronghe") at the Community Level: Integrate resources from community health service centers and community fitness centers. Establish an "exercise prescription" system where doctors prescribe based on health assessments, and community fitness instructors guide execution, forming a closed loop of "screening-assessment-prescription-guidance-feedback."

Institute a "Community Fitness Instructor" System: Place professional, resident sports instructors in every community responsible for daily teaching, activity organization, safety supervision, and nutritional advice (addressing the needs for "professional coach guidance" and "nutritionist advice" identified in the qualitative study), thereby translating scientific exercise into practice.

Develop and Promote "Economical" Fitness Programs: Systematically compile and promote low-cost, easy-to-integrate daily fitness methods (addressing "economic considerations"), such as those identified in the study (e.g., "switching hands when carrying groceries," "raising heels while watching TV"), through video tutorials, pamphlets, etc.

Improve the Macro-System: Policy and Cultural Support Centered on Government and Society

Formulate Preferential Policies: Incorporate per-capita sports funding for the elderly into government budgets and encourage social capital investment in the silver fitness industry. Provide subsidies (e.g., "sports vouchers") for older adults to purchase sports and fitness services, alleviating economic burdens.

Enhance the Precision of Health Knowledge Dissemination: Utilize media channels preferred by the elderly (e.g., TV health programs, WeChat public accounts) for professionals to disseminate easily understandable, anti-"pseudoscience" health information, improving their "health vigilance" and "health participation" capabilities.

Foster a Societal Atmosphere of Active Aging: Through media campaigns, awards, and recognition, change the stereotype that "elderly exercise is just square dancing," showcase diverse, high-quality sports participation in later life, role model positive examples, and inspire greater participation enthusiasm among the elderly population.

5 CONCLUSION

This mixed-methods study demonstrates that physical activity participation exerts a positive influence on health perception among older Chinese adults, with social support playing a critical mediating role[1-3]. The integration of qualitative and quantitative findings provides a holistic perspective on the issue, showing that exercise, when combined with supportive social environments, significantly enhances older adults' awareness, confidence, and positive attitudes toward health[4].
These results carry practical implications for policymakers, healthcare professionals, and community organizations. Efforts to promote active aging should prioritize not only exercise interventions but also the creation of supportive social networks that empower older adults to sustain healthy lifestyles. Future research could further examine longitudinal effects of exercise participation and explore cross-cultural comparisons to broaden the understanding of health perception in aging populations[5-8].

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

AUTHOR CONTRIBUTIONS

Yi Cheng: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – Original Draft.Data Curation, Validation, Writing – Review & Editing.Supervision, Project Administration, Resources.

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THE IDEOLOGICAL ORIGINS OF THE NATIONALIZATION OF RUSSIAN BALLET IN THE FIRST HALF OF THE NINETEENTH CENTURY

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Abstract: The article analyses the process of nationalization of Russian ballet in the first half of the nineteenth century. The study of the development of the Russian ballet is placed within the context of political and social thought in the Russian Empire during the first half of the nineteenth century. The nationalization of Russian ballet refers to the process of forming the Russian ballet style. The process of nationalization of Russian ballet was synchronized with the prevalence of romanticism and nationalism in Russia in the nineteenth century. In Russian theatres, ballet content shifted from the classicalism of Western Europe, represented by ancient Greek mythology, to historical themes that showcased Russian national characteristics. In the field of ballet education, dance and drama were separated, and Russian ballet techniques were formed. Therefore, the development of Russian ballet in the first half of the nineteenth century reflected the transformation of Russian social thought, namely, the shift from Westernization to nationalization and Russification. It is worth noting that Charles Didelot played an important role in the process of nationalizing Russian ballet, and his career and creative journey can be seen as a concentrated display of the development of Russian ballet and social ideological changes.
Keywords: Russian ballet; Nationalization; Ideological origins; Charles didelot; Russian nationalism; Russian education

1 INTRODUCTION

During the critical period of the development of ballet in Russia in the first half of the nineteenth century, it was also an important focus of attention in the field of history. Previous studies on the changes and continuities of Russian ballet in the early nineteenth century exist. Those studies studying this topic analyze the situation from different perspectives. Firstly, scholars focus on ballet education, which is seen in these studies as an important part of Russian dance education. This field of research is represented by T.A. Filanovskaya. She views ballet education as an important part of Russian dance education and places the professionalization of Russian dance education in the first half of the nineteenth century in the context of Romanticism[1]. In another of her articles, she discusses the impact of cultural policy on ballet education[2-3]. Furthermore, the contribution of individual dancers to the development of Russian ballet has been a focus of scholarly attention. For example, Samuel Cross in his article *The Russian Ballet Before Dyagile* takes a detailed look at Charles Didelot's tenure in Russia and argues that he was an important figure in the development of Russian ballet in the early nineteenth century as a style in its own right and as “a factor in the international development of plastic art”[4]. Building upon existing research, this paper will examine the ideological origins of the nationalization of Russian ballet in the first half of the nineteenth century, within the context of social thought and culture, starting with Charles Didelot’s career in Russia and the reforms in ballet education that began in the 1830s.

2 CHARLES DIDELOT AND THE BIRTH OF RUSSIAN NATIONAL ELEMENTS IN BALLET

The history of ballet started in the fifteenth century in Italy; it is a way of socializing and entertainment for nobles during ceremonies during the Italian Renaissance. The history of ballet in Russia started much later. In Russia, ballet appeared in the seventeenth century and finally established itself as a genre in the nineteenth century[5]. After the introduction of ballet to Russia, another major historical point for Russian ballet was the establishment of the Imperial Ballet School by the Empress Anna Ioannovna in 1738, and this school played a major role in the development of Russian ballet history. Since the Petrine Reforms, the Russian Empire exhibited a tendency towards Westernization in its culture, which also influenced the development of Russian ballet in the eighteenth century. Many foreign ballet masters were invited to the Imperial Ballet School in Russia, including French dancer Jean Baptiste Lande and Italian ballet master Canziani. During the eighteenth century, then, choreography was established in Russia by immigrant foreigners[6]. Consequently, Russian ballet before the nineteenth century lacked a distinctive style of its own and primarily imitated Western ballet forms. It was not until the arrival of Charles Didelot in Russia in the early nineteenth century that this situation began to shift.

Charles Didelot is a French ballet master who teaches ballet classes and also creates ballet choreography. He was born into a family of ballet dancers from Sweden on March 28th, 1767. His father was a dancer at the Royal Swedish Ballet. Influenced by his family environment, Didelot started to learn ballet at a very young age. As a young man, Didelot

spent a considerable amount of time studying ballet in Paris under the teacher Jean Dauberval. After becoming a professional ballet dancer, Didelot continued to study dance in Paris under the teacher Jean Dauberval and also performed in several ballets in London in the late 1780s. It was his experience performing in London that brought a classical style to Didelot's ballet[7]. Afterwards, Didelot worked successively in places such as London, Bordeaux, and Paris[8].

In the late eighteenth and early nineteenth centuries, Westernization in the cultural sphere remained a trend in Russian society. In 1801, the former Imperial choreographer Charles Le Picq proposed inviting Charles Didelot to be the new chief choreographer because of Didelot's understanding of ballet and all the achievements Didelot had made in the field of ballet. Because of this, Didelot went to Russia for the first time in 1801 and made his debut as the principal dancer in the Imperial Theater in St. Petersburg. In the following year, 1802, Didelot began serving as head of the theater school attached to the Imperial Theaters in St. Petersburg. In 1806, Didelot suffered a leg injury, and his wife, the talented ballet dancer Ross, passed away, ending his dance career. Didelot's term continued until 1811, and throughout this period, he infused Russian ballet with a classical style and had a significant impact on the development of Russian ballet.

Didelot brought his classical ballets, *Flora and Zephyr,* to Russia in 1803. It premiered in London in 1796 and was later modified and performed at the St. Petersburg Imperial Theatre. The ballet is based on Greek mythology and tells the love story between the god of the west wind, Zephyr, and the flower god Flore[9]. In this ballet, Didelot also used a plot that was quite common at the time. The fickle Zephyr, in love with the goddess of flowers, Flora, was unfaithful to her, admiring other nymphs and dancing with them. Cupid told Flora about this, and the offended goddess hid from Zephyr. Then came remorse. Zephyr swore his fidelity and, after various trials, won back Flora's love[10]. Using ancient Greek gods as the main characters in the plot perfectly showcases Classicism. Similarly, the theme of ancient Greek mythology appears in Didelot's other works, such as his ballet *The Adventures of Telemachus* in 1807 and *Cupid and Psyche* in 1809, which was also based on ancient Greek mythology.

In terms of technological breakthroughs, Didelot utilized the 'flying machine'. This invention was created in 1795 by Didelot himself. The 'flying machine' allows dancers to dance on their toes and also fly in the air, as dancers can be suspended in the air. By making dancers stand on their toes before being lifted, dancers will be seen as weightless. However, this technique was abandoned later as the strings-to-life dancers could be noticed by the audience easily.

In an unforeseen turn of events, Didelot's tenure in Russia was terminated rather abruptly in 1811. This timing aligned with a pivotal moment in the trajectory of Russo-French relations. In 1803, the Napoleonic Wars broke out in Europe. In 1811, the relationship between Russia and France deteriorated rapidly. There is no direct evidence that Didelot left Russia because of his French nationality, as the official reason given was "serious illness"[11]. After his departure, Didelot went to London to continue his ballet career.

Didelot's contributions to Russian ballet were uniquely valuable during that era. While ballet training and performances continued in St. Petersburg after his departure, his post remained vacant. Already in the spring of 1812, Naryshkin, the director of the Imperial Theatres, personally contacted Didelot, inviting him to return to his position in Russia. In the letter, Naryshkin not only expressed his apologies to Didelot but also stated that the Russian people were all longing for his return. After that, in 1815, the administration of the Russian theater reopened discussions with Didelot. On May 7th, in the report to the Committee established for resolving matters pertaining to the Imperial Theatres, Prince P. I. Tyufyakin, the Vice-Director of Theatres noted, that ballet-master Didelot is very useful and necessary for the imperial theaters[12]. Following a warm invitation from the St. Petersburg theatre administration, Didelot returned to Russia in 1816 and once again served as head of the theater school attached to the Imperial Theaters in St. Petersburg.

Significantly, in the second stage of Didelot's career (1816-1829), a shift towards a romantic character in his productions emerged. The dramaturgy of these works focused on ordinary, humanized characters with their passions and internal conflicts. In Russia, Didelot found ballet dancers with emotional openness, commitment to their roles, and a spiritual and emotional embodiment of the characters they portrayed[13]. The Romanticism and Russian national elements present in Didelot's ballets were undoubtedly intertwined with the burgeoning Romantic movement that swept through Europe following the Napoleonic Wars. Guided by Romanticism, many Russian intellectuals, including Pushkin, traveled to southern Russia and the Caucasus to seek their national cultural roots, strengthening their sense of Russian identity.

In 1823, Didelot choreographed the ballet *The Prisoner of the Caucasus*. This ballet was choreographed for his student E.I. Istomina[14], who is a ballet dancer who worked for the Imperial Russian Ballet in the early nineteenth century and is the first Russian dancer en pointe, meaning that she is the first dancer to rise on their toes in Russia. The ballet *The Prisoner of the Caucasus* is a nineteenth-century Russian ethnic themed ballet, based on the poetry of Alexander Sergeevich Pushkin. In fact, *The Prisoner of the Caucasus* is the first play based on a Russian Text in the history of Russian ballet, and this symbolizes the start of ballet based on Russian culture. The poem was written during the Caucasus War in Russia, telling the story of a captured Russian officer in the Caucasus Mountains with the help of the daughter of a mountain chief[15]. This drama has a strong stage presentation of Russian ethnic customs, with Didelot delving into Caucasian folk customs and using Caucasian folk melodies for the music. The costume design is full of exotic features, such as Cherkess robes and short sword accessories, and the dance choreography also incorporates mountain folk dance elements, such as fast rotations and stomping rhythms[16]. For Pushkin himself, the distinctive nature and aesthetic elements of the dance allowed Didelot to express a romantic vision in *The Prisoner of the Caucasus* while simultaneously encapsulating the essence of a truly national theatrical tradition[17].

The Prisoner of the Caucasus concluded Didelot's period of vibrant creative activity, a time of intense dedication and considerable impact. What followed was a downturn, precipitated by a wave of conservatism in Russian society, a time when groundbreaking concepts could no longer find expression. Intriguingly, *The Prisoner of the Caucasus* itself harbored premonitions of transformation, distinct hints of Russian ballet's identity in both the immediate and long-term future[18].

Didelot departed the St. Petersburg Theatre in 1832 following a dispute with Duke Gagarin concerning the staging of the ballet *Syuyumbika, or The Conquest of the Kazan Khanate*. Beginning in the 1830s, the national character of Russian ballet transitioned from the content of productions to the realm of ballet training[19-20].

3 ACCELERATION OF NATIONALIZATION OF RUSSIAN BALLET

After the 1820s conservatism gradually became dominant in Russian social thought, a trend particularly evident in the field of education. In the 1830s, Minister of National Education Uvarov proposed the "Orthodoxy, Autocracy and Nationality" doctrine, often referred to as the "Triad". The seeds of this doctrine were sown during the reign of Alexander I. In 1818, Uvarov, in a speech at a significant meeting of the *Glavnyi Pedagogicheskii Institut*, spoke of love for the fatherland, faith, and the state[21]. In Uvarov's view, the European ideas of liberty, equality, and fraternity, as well as the wave of nationalism, constituted a social storm that "almost involuntarily induced despair." Therefore, defining Russian nationality and disseminating it through education was "a task inextricably linked to the fate of the fatherland"[22]. It is not difficult to notice that, since the 1830s, Russian ballet education also began to develop its own style.

From the introduction of ballet to Russia until the early nineteenth century, the development of ballet education in Russia was based on the continuous learning of Western ballet education.

Peter the Great introduced the idea of Westernization, which means to adopt the culture and practices of Western Europe. Therefore, many German playwrights, Italian opera masters, as well as French and Italian ballet masters, came to Russia, introducing Western European teaching systems to Russia. Professional Ballet Education in Russia started on May 4th, 1738, when the Queen of Russia, Anna Ioannovna, issued a declaration establishing the Imperial Ballet School. In 1826, with the establishment of the Ministry of the Imperial Court, the Imperial Ballet School was incorporated into its extend of jurisdiction, and from this time, the Imperial Ballet School became a closed institution with rules and regulations, include rules such as no student can go out of the school except special permission. German theatre, Italian opera, architecture, and painting, and French and Italian ballet became firmly established in Russia. Foreign actors, musicians, and ballet masters became the first teachers to introduce Western European educational systems to Russia[23]. For this period, from the ballet style to the regulations for the school, Russia was learning from Western Europe's established ballet system. The establishment of professional ballet schools in Russia, frequent tours by foreign ballet companies, and the arrival of famous ballet choreographers and masters from Western Europe laid the foundation for the rapid progress of Russian ballet in the nineteenth century[24].

Since the nineteenth century, foreign and Russian choreographers in Russia drew inspiration from Western Europe, especially French and Italian ballet styles, and started to develop ballet with Russian characteristics, which symbolizes the reform of ballet education in Russia since the 1830s. Ivan Valberkh, the first native-born Russian ballet master, teacher, and choreographer, created many nationalism theme ballets and played a key role in the development of the style of Russian ballet. Ivan Valberkh choreographed ballets based on patriotic themes, such as the War of 1812, and incorporated Russian folk-dance elements into ballet, helping with the development of Russian style ballet. Another ballet choreographer who pushes the nationalism in Russian ballet forward is Adam Glushkovsky. Adam Glushkovsky went to Moscow in 1812. When choreographing, Adam Glushkovsky integrated Russian folk dance and narrative traditions into ballet, and this helps to establish the unique Moscow ballet style. This can be seen in shows he choreographed, such as Ruslan and Ludmila. This shift in the theme and style of choreography shows the rise in nationalism in the ballet world, and the formation of a unique style of Russian ballet change is separate from other styles of ballet.

In the first half of the nineteenth century, nationalization of Russian ballet can also be seen by the fact that the course structure and teaching methods were modified, shaping what is now called the Russian style of ballet. Charles Didelot reformed the education system of Russian ballet. Didelot increased the number of students, extended the training time, and introduced a systematic course structure. This creates a more rigorous and systemic approach for ballet education. When teaching ballet, Didelot emphasizes the combination of technical training and artistic expression, promoting the idea of being a thoughtful dancer. This requires ballet dancers to go beyond mechanical movements, which is different from the ballet training previously, where ballet dancers only did mechanical and technical training. This artistic preference of integrating drama into ballet performance shapes the Russian style of ballet. Together, the discipline and the depth of emotional expression define the Russian ballet identity, making it separate and different from other styles of ballet in other countries.

4 CONCLUSION

The first half of the nineteenth century is the time of the start of nationalist elements in Russian ballet. Various factors, including cultural and social values, political relationships between Russia and other countries, and the development of the Russian ballet standard, cause this.

After reviewing past studies, this paper focuses on a French ballet master, Charles Didelot. Charles Didelot contributed greatly to the establishment of the Russian ballet standard and the emergence of nationalist ideals in the ballet world in Russia, as he helped to standardize the Russian ballet system and choreography that incorporates nationalistic story, theme, and music. This helps to see the development of nationalistic ideology in Russian ballet in the first half of the nineteenth century from a unique and focused perspective, and from this one person, the general trend can be seen.
The transfer of the learning ballet education system from the West to establish the Russian style of ballet in the early nineteenth century also proves the nationalism's role in Russian ballet. Russian ballet initially borrowed heavily from Western techniques and pedagogy, especially from French and Italian. In the early nineteenth century, local Russian ballet masters and foreign ballet masters worked in Russia. They adapted the imported ballet system to fit Russian cultural values and aesthetics, creating a distinct Russian style of ballet that served as a symbol of Russia.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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EXPLORATION ON THE COLLABORATIVE CONSTRUCTION OF ANTI-FRAGILITY IN HIGHER VOCATIONAL COMPUTER EDUCATION UNDER THE BACKGROUND OF DIGITAL TRANSFORMATION

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Abstract: Under the global wave of digital transformation, higher vocational computer education is facing dual challenges from technological iterations and industry demands. New technologies such as cloud computing and artificial intelligence are reshaping the professional landscape and subverting traditional talent cultivation models, creating a complex situation of opportunities and challenges. This study takes the dynamic feedback mechanism of system dynamics as the analytical framework, combines the symbiotic evolution theory of educational ecology, and innovatively introduces Taleb's anti-fragility theory as the core methodology. From four dimensions: innovation of teaching models, optimization of teaching staff, deep integration of industry and education, and coordination of school-enterprise resources, a collaborative development strategy model with adaptive adjustment capabilities is constructed. The aim is to enhance the resilience and evolutionary potential of higher vocational computer education in an uncertain environment. Experimental results show that students in the experimental group significantly outperform those in the control group in terms of theoretical application and practical innovation abilities, verifying the effectiveness of the model in improving educational adaptability and evolutionary capabilities. This research aims to assist higher vocational computer education in adapting to the development of the digital economy and provide theoretical and practical references for cultivating high-quality applied talents.
Keywords: Digital transformation; Higher vocational computer education; Anti-fragility; Collaborative construction; Educational reform

1 INTRODUCTION

Against the backdrop of digital technology reshaping the global economic and social landscape, higher vocational computer education, as a core link in cultivating applied digital talents, faces dual challenges of rapid technological iterations and volatile industrial demands. McKinsey predicts that by 2025, the global digital skills talent gap will reach 290 million, posing higher requirements for employment-oriented higher vocational computer education [1]. Traditional education models struggle to cope with technological changes and demand fluctuations, urgently needing to build a new educational ecosystem. Taleb's anti-fragility theory suggests that systems can not only withstand risks in the face of uncertainties but also upgrade through fluctuations. By introducing this theory into higher vocational computer education and constructing a collaborative mechanism between education and industry, promoting the dynamic adaptation of teaching resources, courses, and practical platforms, the continuous evolution of the education system can be achieved [2]. Based on the anti-fragility theory, this paper analyzes the vulnerabilities of higher vocational computer education, explores the collaborative paths among educational, industrial, and policy entities, and provides references for the development of vocational education.

2 THEORETICAL BASIS

2.1 Taleb's Theory

Taleb's tripartite system theory model of vulnerability, resilience, and anti-fragility, proposed in Antifragile: Things That Gain from Disorder, explains the laws of how systems respond to uncertainties. Vulnerable systems are sensitive to external shocks; for example, traditional closed teaching is difficult to adapt to educational changes brought about by rapid technological iterations. Resilient systems have self-healing capabilities, such as systems integrated with practical teaching, which can maintain system stability. Anti-fragile systems break through traditional adaptation theories and can achieve evolution under pressure [3]. The core of this theory is that systems gain energy from shocks, advocating the promotion of system evolution through controlled disturbances and dynamic feedback. This provides theoretical support for constructing the anti-fragility system of higher vocational computer education. In practice, vulnerability points can be identified through fault simulation experiments and multi-dimensional reflection mechanisms to promote the matching of teaching with industry demands. Meanwhile, elements such as teaching staff capabilities and industry-education integration can be refined to build an adaptive educational ecosystem.

2.2 Theory of Vocational Competence Development

Rooted in the theories of dynamic capabilities and resilience, and deeply integrating the cutting-edge concept of embedding anti-fragile vocational competencies into professional qualities, a dual-core driving model of technical and non-explicit capabilities is systematically constructed. In the dimension of technical capabilities, the focus is on core areas of computer science such as programming development, algorithm design, and system architecture. Through the dynamic design and continuous optimization of a modular curriculum system, the dynamic evolution and organic integration of knowledge and skills are achieved, ensuring that students can keep up with industry technology trends. In terms of non-explicit capabilities, adaptability and resilience are regarded as core elements. Adaptability corresponds to the high-order cognitive ability to actively solve complex problems, emphasizing students' rapid learning and innovative thinking in the face of technological iterations and industry changes. Resilience focuses on the psychological adjustment ability to break through adversity, focusing on cultivating students' stress resistance and psychological resilience in the face of career development difficulties [4]. During the research process, the Delphi method and the analytic hierarchy process are comprehensively used. Through multiple rounds of expert consultations and scientific quantitative analysis, 12 key elements such as data sensitivity, technological foresight, and innovative thinking are accurately identified. A scientific and comprehensive evaluation index system is constructed from four dimensions: knowledge reconstruction, skill transfer, psychological adjustment, and environmental adaptation [5]. This system not only provides solid theoretical support for the reform of higher vocational computer education but also aims to cultivate compound talents with both technical expertise and excellent risk resistance capabilities to meet the urgent needs of the industry for high-quality computer talents in the context of digital transformation.

3 IDENTIFICATION OF CORE ELEMENTS OF ANTI-FRAGILITY IN HIGHER VOCATIONAL COMPUTER EDUCATION UNDER DIGITAL TRANSFORMATION

3.1 Basis and Logic of Element Identification

Taking curriculum design, teaching organization, and student evaluation as the core research dimensions, combined with the characteristics of rapid technological iteration and uncertain job requirements in digital transformation, key elements are refined based on the principles of theoretical adaptation and practical relevance. In curriculum design, in response to the rapid development of cutting-edge technologies such as artificial intelligence and cloud computing, a modular and dynamically updatable curriculum system is constructed to ensure that teaching content keeps pace with industry technology evolution [6]. In teaching organization, project-based learning and blended teaching models are introduced to create a teaching paradigm that integrates theory, practice, and innovation, enhancing students' ability to solve complex problems [7-8]. Student evaluation breaks through traditional quantitative assessment, and a multi-dimensional evaluation system covering process, project results, and professional qualities is constructed [9]. Through the practice of these three dimensions, the impact of digital transformation on higher vocational computer education is analyzed, and the key nodes of educational adaptability are positioned based on the theory of anti-fragility to solve problems such as curriculum lag and weak practice, providing support for the construction of an anti-fragility collaborative mechanism [10].

3.2 Construction of the Core Element System

3.2.1 Core elements of the collaborative construction of anti-fragility in higher vocational computer education under digital transformation

The core element system of the anti-fragility collaboration in higher vocational computer education presents the characteristics of multi-dimensional collaborative evolution. Based on the theoretical framework of the Complex Adaptive System (CAS), curriculum structure design achieves self-adaptive coupling between educational supply and industrial demand through the dynamic cycle mechanism of modular knowledge unit reorganization, interdisciplinary task group construction, and industry-education integration [11]. In the innovation of teaching organization paradigms, with the core logic of trial and error and collaborative repair, through project-based learning, in-depth analysis of failure cases, and reverse instructional design, a two-way cultivation path for students' knowledge reconstruction and ability iteration is constructed. The construction of the evaluation system introduces a non-linear dynamic feedback model to build a process evaluation matrix covering dimensions such as cognitive development, practical innovation, and collaborative effectiveness. Through the collaborative participation of multiple evaluation subjects, a continuous improvement loop is formed [12]. The support guarantee system focuses on the cultivation of digital literacy of the teaching staff and the ecological construction of the school-enterprise collaborative innovation network. Relying on the two-way empowerment mechanism of the education chain and the industry chain, a dynamic adaptive collaborative system of anti-fragility in higher vocational computer education is finally formed.

3.2.2 Analysis of element correlation mechanisms

Under the background of digital transformation, deepening the construction of the internal and external collaborative correlation system is the key to implementing the collaborative construction mechanism of anti-fragility in higher vocational computer education. Internally, a highly tolerant teaching mechanism needs to be constructed to support the dynamic self-adaptive curriculum system. Specifically, professional courses can be modularly decomposed, elastic learning nodes can be integrated, and a three-stage progressive project-based learning model of foundation building

through basic tasks, improvement through advanced challenges, and expansion through innovative practice can be adopted to achieve the integration of learning and application [13]. At the same time, a growth-oriented evaluation system is established, incorporating cognitive reconstruction, strategy optimization, and error transformation abilities into process evaluation to form a closed-loop feedback system for curriculum design, practical teaching, and effectiveness evaluation. Externally, the construction of a three-dimensional teacher professional development system is taken as the core to inject sustainable impetus into the dynamic iteration of courses [14]. Specifically, guided by scientific teacher professional ability standards, teachers' professional qualities are improved through multiple channels such as on-campus training, corporate internships, and academic seminars. With the coordination of the professional construction committee, a dynamic curriculum update mechanism is established. In practical teaching, school-enterprise cooperation is deepened to create a teaching model that integrates project chains and curriculum groups, implement the dual-tutor system, and build an intelligent industry-education integration platform to optimize the allocation of practical teaching resources.

4 THEORETICAL MODEL OF THE COLLABORATIVE CONSTRUCTION OF ANTI-FRAGILITY IN HIGHER VOCATIONAL COMPUTER EDUCATION UNDER DIGITAL TRANSFORMATION

4.1 Model Framework Design

Based on the coupling relationship between digital transformation and higher vocational computer education, this paper innovatively constructs a theoretical model with one goal layer, four core dimensions, and two-way collaboration, as shown in Figure 1.

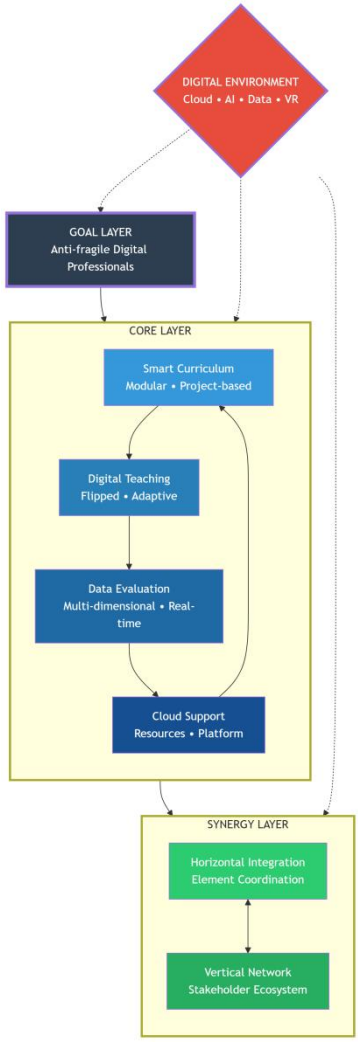

Figure 1 Framework Design of the Theoretical Model for the Collaborative Construction of Anti-fragility in Higher Vocational Computer Education under Digital Transformation

Goal Layer: In the context of rapid digital technology iteration and dynamic changes in industry talent demand, cultivating higher vocational computer professionals with anti-fragile attributes is the key to optimizing the adaptability of the educational ecosystem to digital transformation. By reconstructing the educational paradigm, it helps students maintain stable professional capabilities in complex technical and industry environments and builds an ability system

that actively adapts to technological changes and promotes the improvement of professional qualities to cope with the challenges and opportunities brought by digital transformation.

Core Layer: Based on the theory of complex adaptive systems and combined with the requirements of digital transformation, the anti-fragility of higher vocational computer education is systematically improved through the multi-dimensional collaboration of curriculum structure optimization, teaching organization innovation, and evaluation system reconstruction. Curriculum structure optimization closely follows the trends of technologies such as cloud computing and artificial intelligence. With modular curriculum groups and project-based units as the framework, content is dynamically updated, enterprise cases are embedded, and immersive workshops are created to ensure that the curriculum is synchronized with the industry. Teaching organization innovation constructs a problem-oriented elastic paradigm, integrates collaborative learning and flipped classrooms, uses digital tools to establish an instant feedback mechanism, and optimizes the process through dynamic grouping and blended teaching. The reconstruction of the evaluation system establishes a three-dimensional evaluation model including process, value-added, and multiple subjects, introduces enterprise experts, and uses big data to achieve dynamic and precise evaluation oriented by students' digital ability growth [15]. The construction of the support system relies on the theory of government-school-enterprise-industry collaborative innovation, integrates digital resources, and builds an educational resource sharing platform and industry-education integration training bases. Cloud computing is used to build an online learning resource library, virtual reality is used to create virtual training scenarios, and a long-term mechanism for cultivating teachers' digital teaching capabilities is established. The four elements collaborate and dynamically adjust to form a collaborative construction mechanism for the anti-fragility of higher vocational computer education.

Collaboration Layer: Relying on the two-dimensional architecture of horizontal and vertical collaboration, closely following the characteristics of digital transformation, deep collaboration among educational elements and participating subjects is achieved. Horizontal collaboration focuses on curriculum structure, teaching organization, evaluation system, and support system. Through industry-education collaboration, curriculum design is optimized, and digital disassembly of industry projects drives the integration of theory and practice teaching. Intelligent algorithms and big data technologies are used to construct a closed loop for evaluation and resource allocation, and the training and teaching staff systems are improved. Vertical collaboration builds a collaborative network among colleges, enterprises, teachers and students, and industry experts. Schools and enterprises jointly build industrial colleges, unify standards, and develop training systems. Teachers and students interact through online platforms, and industry experts empower through online lectures, promoting the deep integration of the education chain, talent chain, and industry chain to adapt to the needs of digital transformation.

4.2 Model Operation Logic

With the digital transformation driving profound changes in the social and economic system, the structural contradictions in the higher vocational computer education system have become increasingly prominent. The update speed of the textbook system is far behind the development of cutting-edge technologies such as artificial intelligence, cloud computing, and big data, resulting in a disconnection between teaching content and the forefront of industry technology. There is a structural mismatch between the talent cultivation standards and the needs of industrial digitization, and graduates' engineering practice and innovation capabilities hardly meet the requirements of enterprises, exacerbating the imbalance between talent supply and demand [16].

Therefore, this paper proposes the construction of a three-in-one collaborative support system, focusing on the professional development of teaching staff and the integration of school-enterprise resources. In terms of teaching staff construction, a regular industry technology training and corporate internship system is established to improve teachers' practical teaching abilities and technical sensitivity. In terms of school-enterprise cooperation, deep integration of the education chain and the industry chain is promoted through ways such as jointly building training bases and developing courses [17]. At the same time, a fault-tolerant repair training model based on constructivism is introduced to encourage students to expose cognitive biases in practice and achieve cognitive reconstruction through system feedback. A multi-dimensional evaluation system covering knowledge, skills, and qualities is constructed to establish a three-dimensional evaluation framework from aspects such as theoretical mastery, project practice, and professional qualities.

This collaborative system operates based on the logic of shock perception, dynamic response, structural remodeling, and ability leap, aiming to create an anti-fragile development mechanism for higher vocational computer education. When the external technical environment or industry demand changes, the system can quickly perceive the shock through multi-source information collection, use dynamic response to optimize resource allocation and reconstruct the educational structure, promoting the educational system to transform from passive adaptation to active evolution and achieving the sustainable development of the educational ecosystem.

5 COLLABORATIVE CONSTRUCTION PATHS FOR THE ANTI-FRAGILITY OF HIGHER VOCATIONAL COMPUTER EDUCATION IN THE DIGITAL TRANSFORMATIONL

5.1 Collaborative Adaptation Path between Curriculum Structure and Digital Technologies

5.1.1 Building a modular and dynamically updatable curriculum system

Against the backdrop of the accelerated digital transformation, core technologies such as artificial intelligence, cloud computing, and big data are continuously evolving. These advancements not only expand and deepen the technical

fields but also drive profound changes in industrial forms and talent demands. In this context, building a modular and dynamic curriculum system through in-depth school-enterprise collaboration has become a crucial path to precisely align education with industrial needs [18].

The construction of the curriculum system is driven by school-enterprise collaboration. Based on industrial links such as technology research and development, application practice, and operation and maintenance management, a progressive modular structure is established to achieve an organic unity of knowledge imparting and ability cultivation. Through collaborative mechanisms such as joint research and enterprise technology demand collection, schools and enterprises jointly establish a dynamic optimization mechanism for industry technology monitoring and curriculum content iteration. A joint teaching and research team composed of enterprise technical experts and university teachers uses methods such as the Delphi method and technology roadmap analysis to jointly assess the evolution trend of industrial technologies and talent requirement standards, ensuring that the curriculum system always keeps pace with the forefront of industry development. On this basis, 20%-30% of the curriculum content is dynamically updated each semester, integrating new technologies, tools, and standards into teaching in a timely manner, thus achieving synchronous resonance between educational supply and industrial demand.

5.1.2 Design of real project-based teaching tasks with interdisciplinary elements

The digital transformation has given rise to the trend of multi-technology integration, with scenarios such as the combination of artificial intelligence and big data, and cloud computing enabling software development emerging continuously. To cultivate composite talents adaptable to complex technical environments, it is necessary to design real project-based teaching tasks integrating multi-technology through the school-enterprise collaborative education mechanism.

During the project design process, schools and enterprises jointly construct a fuzzy goal-oriented design model and a resource-constrained practical strategy. By categorizing and defining failure types and opening up solution design, students are guided to break through the boundaries of technical cognition. By setting a 30-day development cycle, quantifying computing resources, and providing technical support, the time and resource constraints of real enterprise projects are simulated. During project implementation, students need to continuously optimize technical solutions and reconstruct team collaboration processes under the guidance of school-enterprise mentors amidst dynamically changing technical requirements, enhancing their dynamic adaptability and technological innovation capabilities in solving complex engineering problems within real business scenarios, thus achieving deep integration of school-enterprise collaborative education [19].

5.2 Collaborative Integration Path between Teaching Organization and Anti-Fragility Concepts

5.2.1 Implementing the integrated project-based review teaching model

In the wave of digital transformation, to enhance the anti-fragility of higher vocational computer education, this paper constructs a spiral teaching model centered around students' trial-and-error and team collaborative repair. This model covers courses such as programming design and database management and consists of four stages: project initiation, trial-and-error practice, collective review, and strategy optimization. At the project initiation stage, previous failure cases are introduced through a digital platform, and students are guided to predict risks and analyze scenarios using risk assessment theory. During the trial-and-error practice stage, digital simulation technology is used to create error scenarios, and students complete code review and debugging through group collaboration, exercising their problem-solving abilities. In the collective review stage, mind maps are utilized to visualize knowledge, and general solutions are extracted through cross-group comparison. In the strategy optimization stage, solutions are optimized based on review results, and a question bank for error prevention is established using knowledge management theory to form a preventive knowledge system. Digital tools are deeply integrated into each link. Through the deconstruction and reconstruction of failure cases, the integration of teaching and practice is achieved [20], cultivating students' abilities in problem diagnosis, team collaboration, and knowledge transfer, and promoting the high-quality development of higher vocational computer education.

5.2.2 Integration of reverse instructional design and digital tools

Relying on a virtual simulation teaching platform, a full-link digital transformation typical technical failure scenario library is constructed. The scenarios cover basic failures such as system crashes and data loss, as well as complex situations such as cyber security attacks, microservice cascading failures, and abnormal cloud computing resource scheduling. In teaching, the OBE (Outcome-Based Education) reverse instructional design is adopted, transforming enterprise operation and maintenance work orders into cases. Through five stages - failure observation, impact assessment, technical tracing, solution design, and verification - students are guided to learn knowledge such as operating system principles and data recovery algorithms, as well as skills such as log analysis and emergency response in reverse from the perspective of failure requirements [21].

This model drives knowledge construction through problems. With a gradient-increasing task system, combined with the real-time feedback and dynamic evaluation of the virtual simulation platform, it cultivates students' anti-fragility thinking. For example, in the system crash scenario, students need to comprehensively consider data protection, service recovery, and resource scheduling, forming a closed-loop thinking of risk identification, adaptability to changes, and utilization of fluctuations during the problem-solving process [22]. At the same time, school-enterprise cooperation is deepened, and enterprise experts are invited to participate in scenario design and teaching evaluation. With the practical

experience of enterprises, it is ensured that teaching content keeps up with the development of industry technologies, achieving digital collaboration between education and enterprise needs.

5.3 Collaborative Matching Path between Evaluation System and Ability Growth

5.3.1 Constructing a three-dimensional process evaluation index system

Based on a three-dimensional evaluation framework of adaptability, resilience, and growth feedback, the index system is deconstructed from three dimensions: dynamic adaptation, crisis handling, and sustainable development. In the technical adaptability dimension, a six-item secondary index quantification system is constructed, focusing on the cognitive cycle of new technologies and the application efficiency of open-source frameworks, dynamically evaluating the adaptability of the teaching system to cutting-edge technologies. In the failure resilience dimension, a four-core index evaluation model is established, paying attention to the speed of failure diagnosis and response and the reconstruction cycle of solutions. In software development training, the failure event log system records the repair duration, analyzes team collaboration and solution paths, and forms a case library. In the comprehensive growth dimension, a cross-project ability matrix evaluation model is adopted. Based on five indicators such as Git code contribution and the quality of project review reports, the development trajectory of students' abilities is tracked. Evaluation data is collected in real-time through the growth archive system, and ability maps are generated by visualization tools to achieve intelligent analysis of learning process data.

5.3.2 Establishing a multi-subject collaborative and dynamic feedback evaluation mechanism

Against the backdrop of the digital transformation reshaping the industrial and educational landscapes, the innovation of the evaluation system for higher vocational computer education is the key to industry-education integration. A three-dimensional evaluation system centered around teachers' professional development, students' metacognitive self-assessment, and enterprise job competence is constructed. Using quantitative tools such as project reviews and ability matrices, dynamic evaluations are carried out 2-3 times per semester. The Delphi method and analytic hierarchy process are used for teachers' professional development evaluation, constructing indicators from teaching design, methods, and effects [23]. Students' metacognitive self-assessment uses the Likert scale to construct a monitoring scale [24]. The evaluation of enterprise job competence is based on professional standards, and a model is constructed using the behavioral event interview method. At the same time, a closed-loop of evaluation, feedback, and improvement is formed, and the results are integrated into curriculum reconstruction and teaching innovation.

5.4 Collaborative Guarantee Path between Support Systems and Core Elements

5.4.1 Building a teaching staff that integrates digital and anti-fragility concepts

Teachers' digital teaching abilities are enhanced through a multi-dimensional mechanism. An enterprise attachment practice system is established to normalize teachers' participation in enterprise digital transformation projects, enabling them to accumulate experience in scenarios such as industrial Internet development and intelligent system integration and transform it into teaching resources. The thematic teaching and research mode conducts workshop training guided by anti-fragility theory, helping teachers master skills such as teaching objective adjustment and fault-tolerant task design [25]. The knowledge inheritance and innovation mechanism realizes knowledge transfer and innovation through a gradient mentoring system, seminars, etc., and an incentive mechanism is established to promote the professional growth of the team and adapt to the needs of digital transformation.

5.4.2 Building a school-enterprise collaborative resource sharing platform

School-enterprise cooperation is deepened, and a digital platform for educational resources is constructed to create a technical dynamics database and a practical case database. The technical dynamics database tracks the update of cutting-edge technologies, industry achievements, and standards through enterprise data interfaces and artificial intelligence collection technologies. The practical case database establishes a full-process collection system, collecting multi-modal data such as enterprise technical failures and project documents. Schools and enterprises jointly formulate resource specifications and standards to ensure that resources meet teaching needs and enhance the anti-fragility of higher vocational computer education [26].

6 EXPERIMENTAL VERIFICATION AND ANALYSIS

To verify the effectiveness of the collaborative construction model for the antifragility of computer education in higher vocational colleges under the background of digital transformation, a comparative experiment was designed. Two higher vocational colleges with similar teaching resources were selected. College A, adopting the traditional computer education model, served as the control group, while College B, implementing the education reform plan based on the collaborative construction of antifragility, served as the experimental group. The experiment lasted for one semester, and the teaching effects were evaluated through multi-dimensional indicators. The specific data are shown in Figure 2 and Figure 3.

Academic Performance: Compare the average scores and excellent rates of students from the two colleges in courses such as computer fundamentals, programming languages, and project practice.

Skill Competitions: Count the number and grades of awards won by students in computer-related competitions at the provincial level and above.

Enterprise Feedback: Collect satisfaction scores from partner enterprises regarding the digital tool application and problem-solving abilities of graduates.
Innovation Ability: Evaluate the number and innovation level of digital projects independently developed by students.

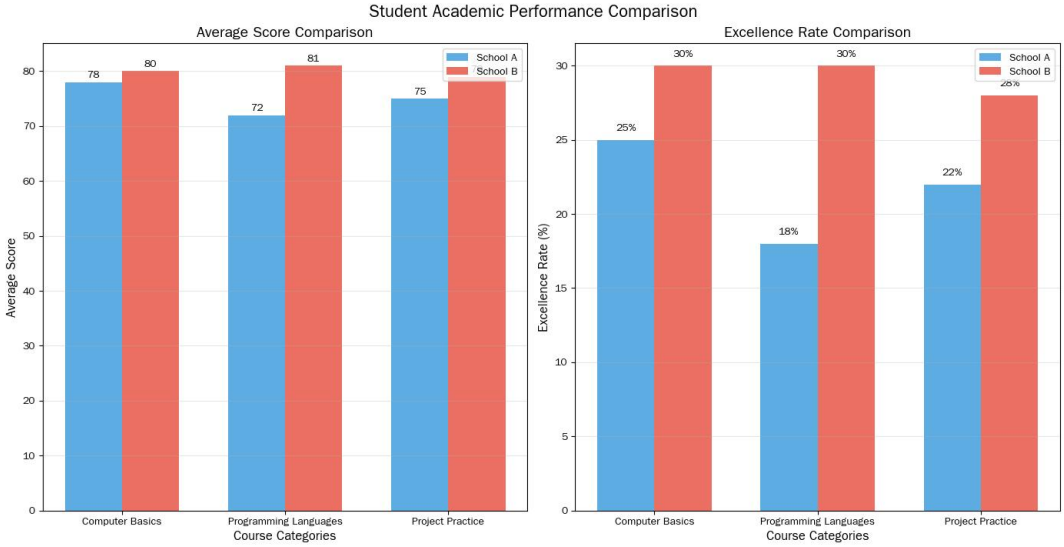

Figure 2 Comparison of Students' Academic Performance

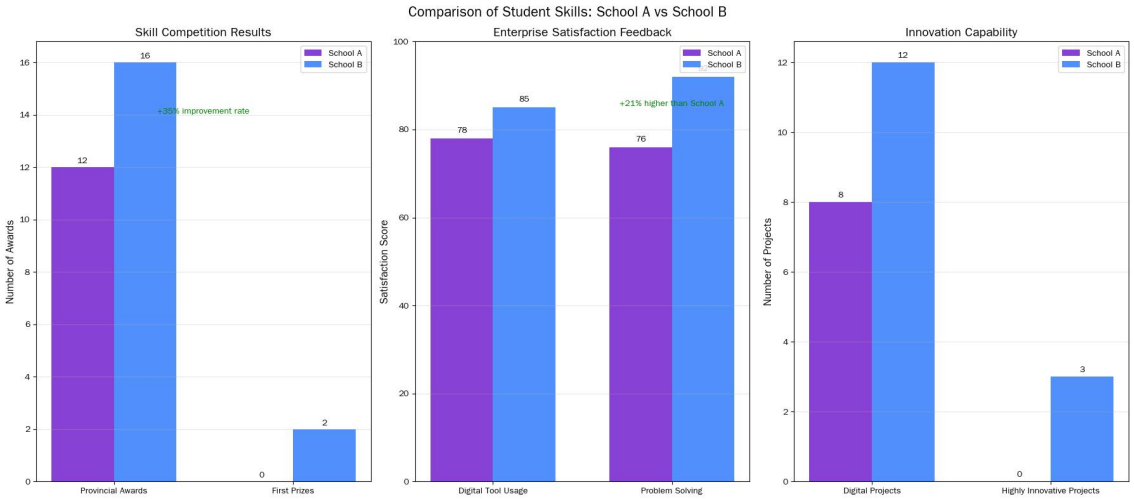

Figure 3 Comparison of Students' Performance in Skills Competitions, Enterprise Feedback, and Innovation Ability

The experimental results show that the average score of students from School B in programming language courses increased by 12%, the provincial competition award - winning rate increased by 35%, and the enterprise satisfaction score for their ability to solve complex problems was 21% higher than that of the control group. A significance test using SPSS ($p<0.05$) verified that the anti - fragile collaborative construction model has a significant effect on improving students' digital capabilities and professional adaptability, providing data support for the practical application of the model.

7 CONCLUSION AND OUTLOOK

This study has achieved breakthroughs both theoretically and practically. Theoretically, it has systematically sorted out the laws of higher vocational computer education, constructed a one-layer goal, four-dimensional core, and two-way collaboration model, and improved the educational system of anti-fragility theory. In practice, it has addressed industry pain points through curriculum updates, teaching innovations, and evaluation reconstruction. However, there are limitations, such as insufficient consideration of external variables like policy response mechanisms and lack of attention to the specific needs of different majors. In the future, it is necessary to supplement influencing factors and iterate the model.
Future research will be advanced from theoretical, practical, and international perspectives. Theoretically, it will explore the coupling mechanism between digital transformation and anti-fragility, and introduce cutting-edge methods to quantify the relationships among various elements. In practice, the model will be extended to majors such as higher vocational electronic information and artificial intelligence, optimized through pilot projects, and promoted for cross-

domain applications. Internationally, in light of global vocational education reforms, research results will be shared through conferences, papers, and cooperative projects, offering a Chinese perspective.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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INFLUENCING FACTORS OF EMPLOYABILITY AMONG STUDENTS IN HIGH-LEVEL UNIVERSITIES IN GUANGDONG: AN EMPIRICAL ANALYSIS BASED ON THE USEM MODEL

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Abstract: With the continuous advancement of China's Double First-Class initiative, high-level universities in Guangdong have been playing an increasingly prominent role in promoting regional economic development and cultivating high-level talent. Employability has become a key indicator for evaluating the quality of talent training in higher education and a critical issue in the development of high-level universities. Based on the USEM model, this study examines the influence mechanism of four dimensions, namely understanding, skills, self-efficacy, and metacognition, on university students' employability by constructing a structural equation model. Data were collected through 361 valid questionnaires from students in Guangdong and analyzed using partial least squares structural equation modeling (PLS-SEM) for hypothesis testing and path analysis. The results show that skills and self-efficacy have a significant direct positive impact on employability. Although understanding and metacognition do not exhibit a direct significant effect on employability, they exert important indirect influences through the mediating role of skills. The model demonstrates a good fit, supporting the applicability of the USEM model in this research context. This study not only expands the empirical application of employability theory in the context of higher education but also provides a basis and practical recommendations for high-level universities in Guangdong to optimize talent training models, enhance skill development and self-efficacy, and improve employability support systems.
Keywords: High-level universities; Employability; USEM model

1 INTRODUCTION

As China's higher education enters a new stage of high-quality development, building a group of high-level universities has become a key initiative to enhance national competitiveness and strengthen strategic talent support[1]. As a leading province in economic and innovative development, Guangdong has continuously implemented the high-level university construction plan, aiming to establish talent cultivation hubs with international influence[2]. Against this backdrop, the employment quality of university graduates has gradually replaced traditional employment rate metrics, becoming a core criterion for evaluating the effectiveness of higher education institutions. Employability, reflecting graduates' career adaptability and development potential, has garnered increasing attention from the government, universities, and society at large[3].Current research on university students' employability has evolved from a narrow focus on knowledge and skill acquisition to a more comprehensive emphasis on integrated competencies and psychological cognitive resources[4].The USEM model (Understanding, Skills, Self efficacy, Metacognition), which encompasses the four dimensions of Understanding, Skills, Self efficacy, and Metacognition, provides a well-established theoretical framework for explaining the formation mechanism of employability[5]. This model not only addresses the development of explicit skills but also highlights the role of deeper cognitive foundations, motivational regulation, and metacognitive strategies, aligning with the growing demand for versatile and adaptive talents in a rapidly changing society. Nevertheless, empirical studies based on the USEM model remain relatively limited in China, particularly those focusing on students in high-level universities. This study targets students from high-level universities in Guangdong Province and, based on the USEM model, proposes the following hypotheses: Understanding and Metacognition indirectly affect Employability by promoting Skills development, while Skills and Self-efficacy exert a direct positive influence on Employability. The study employs partial least squares structural equation modeling (PLS-SEM) to empirically examine the path relationships among these variables. The aim is to clarify the mechanisms through which these four dimensions affect employability, thereby providing a theoretical basis and empirical support for optimizing talent cultivation systems in high-level universities.

2 LITERATURE REVIEW

2.1 Research on the Construction of High-Level University Groups

In recent years, China's Double First-Class initiative has facilitated a shift in the national higher education system from quantitative expansion to qualitative enhancement. As a key government-supported talent development program, the "High-Level University Development Plan" in Guangdong Province aims to establish a group of universities with international competitiveness and regional influence, thereby providing intellectual and talent support for regional

socioeconomic development[6]. Existing studies have largely focused on macro-level approaches such as elevating institutional prestige, optimizing disciplinary structures, and strengthening research innovation capabilities. Nevertheless, systematic research remains scarce regarding how talent cultivation in higher education aligns with the needs of regional economic development and industrial upgrading, particularly from the perspective of core student competency development and employment orientation. In the current context where "high-quality employment" has become a central objective and performance indicator in higher education, improving students' employability has transcended individual development and become a crucial measure of institutional educational quality and collective competitiveness[7]. Therefore, integrating the development of high-level universities with the cultivation of employability, and further investigating the intrinsic relationship and interactive mechanisms between the two, will not only contribute to the theoretical discourse on higher education management but also hold significant practical value for optimizing regional talent supply and facilitating university-industry collaboration in education. This study, grounded in the USEM model and adopting a multidimensional capability framework, systematically explores the formation pathways and enhancement strategies of employability among students in high-level universities.

2.2 Research on the Structural Connotation and Measurement of College Students' Employability

Employability, first proposed by British scholars Yorke and Knight, refers to the integrated manifestation of the knowledge, skills, attitudes, and traits that individuals require to obtain, maintain, and develop their careers[8]. Academic perspectives on the construct's dimensionality are diverse and can be broadly categorized into three approaches: (1) a skill-oriented perspective, which emphasizes observable and trainable elements such as hard skills (e.g., professional knowledge and language proficiency) and soft skills (e.g., communication and teamwork); (2) a competency integration perspective, which views employability as a composite of knowledge, ability, emotion, and attitude, focusing on the coherence between personal qualities and career adaptability ,and (3) a developmental perspective, which conceptualizes employability as a dynamic process involving self-awareness, self-regulation, and environmental adaptation[9].In the Chinese context, existing research generally emphasizes the importance of aligning employability with the quality of higher education, curriculum design, and career guidance services[10]. However, current explorations into the internal structure of employability remain somewhat abstract and lack operational clarity, underscoring the need for systematic theoretical modeling and empirical validation. To address this gap, this study adopts the USEM model (Understanding, Skills, Self-efficacy, Metacognition) and constructs a multidimensional framework of employability based on these four dimensions. The aim is to provide a theoretical foundation and empirical pathway for the systematic evaluation and cultivation of employability among students in high-level universities.

2.3 Theoretical and Applied Research on the USEM Model

Knight and Yorke proposed the USEM model, which conceptualizes employability through four core dimensions: (1) Understanding, referring to the comprehensive grasp and practical application of professional knowledge; (2) Skills, encompassing both general and discipline-specific capabilities; (3) Self-efficacy, defined as an individual's confidence and perceived control in successfully accomplishing tasks; and (4) Metacognition, which includes the ability to monitor, regulate, and reflect on one's cognitive processes[8]. The model emphasizes that these dimensions are not isolated but interact synergistically to enhance students' capacity to navigate complex professional environments and achieve sustainable development. Rather than focusing solely on what students "can do," the USEM model also highlights their potential for performance improvement and future adaptability. Globally, the USEM model has been extensively applied in higher education curriculum evaluation, vocational education reform, and longitudinal research on student competency development[11]. In contrast, empirical studies within the Chinese context remain limited, particularly those examining the model's full structural pathways using analytical methods such as structural equation modeling. Although some scholars have drawn on certain dimensions of the USEM framework to investigate the relationship between educational quality and employability, the integrated structure and multidimensional mechanisms of the model have not yet been systematically tested. Furthermore, within the specific setting of high-level university groups, empirical evidence regarding the application of the USEM model to analyze and enhance student employability is still lacking. Therefore, this study targets students from high-level universities in Guangdong and employs structural equation modeling to examine the mechanisms through which the four USEM dimensions influence employability. The findings aim to provide both theoretical support and practical insights for the localization of the USEM model and its application in fostering employability within high-level universities.

2.4 Research Innovation

Overall, existing research exhibits notable limitations in the following aspects: (1) Weak theoretical integration: (2) Limited empirical methodologies: There is a scarcity of in-depth research employing structural equation modeling—such as partial least squares SEM (PLS-SEM),to analyze pathways and weigh the influence of various dimensions on employability; (3) Inadequate contextual and population adaptation: Current discussions are predominantly situated within general higher education institutions or macro-level policy analyses, with a lack of empirical focus on the specific context of high-level university groups. In response to these research gaps, this study adopts the USEM model as its theoretical foundation to construct a structural model of the influencing mechanisms of

college students' employability and conducts empirical validation using a sample of students from high-level universities in Guangdong. The innovation of this research lies in its systematic examination of the explanatory power of the USEM model within the context of high-level universities in China. By applying PLS-SEM, the study elucidates both the direct and indirect pathways through which various dimensions affect employability, thereby providing empirical support for the localized application of the model. Furthermore, the findings offer quantitatively grounded insights and practical guidance for enhancing talent cultivation systems and employability development strategies in high-level universities.

3 THEORETICAL FOUNDATION AND RESEARCH HYPOTHESES

3.1 Theoretical Foundation

The USEM model, proposed by Knight and Yorke, is a widely adopted theoretical framework for assessing employability in higher education[8]. The model posits that the employability of university students is not merely a reflection of isolated skills, but a multi-dimensional structure consisting of four core elements: understanding, skills, self-efficacy, and metacognition. These components collectively shape an individual's employment outcomes and career adaptability (variables are presented in Table 1. A key strength of the USEM model lies in its integrated and developmental perspective, it focuses not only on whether students possess certain competencies, but also on their capacity to further develop those abilities, highlighting the role of agency and potential. This aligns particularly well with the talent development goals of high-level universities that emphasize high-quality employment. Based on this model, this study targets students from high-level universities in Guangdong Province and employs a structural equation modeling (SEM) approach to investigate the mechanisms through which the four constructs—understanding (U), skills (S), self-efficacy (E), and metacognition (M),collectively influence employability (E).

Table 1 Variable

Target	Dimensions	Evaluation of recognition points
CEmployability(EM)	Understanding (U)	Professional knowledge (U1)
		Identify the problem (U2)
		Logical analysis (U3)
		Professional Transformation (U4)
		Broad knowledge (U5)
	Skills (S)	Organization and Coordination (S1)
		Data analysis (S2)
		Innovation ability (S3)
		Communication skills (S4)
		Teamwork (S5)
		Adaptability (E1)
	Self efficacy (E)	Self-adjustment (E2)
		Continuous action (E3)
		Stress resistance (E4)
		Self-confidence (E5)
	Metacognition (M)	Self-reflection (M1)
		Career Planning (M2)
		Inner cultivation (M3)
		Self-control (M4)
		Self-awareness (M5)

3.2 Understanding and Skills

Understanding refers to students' comprehensive grasp and systematic integration of professional knowledge, principles, and real-world application contexts.In high-level universities, where disciplinary knowledge systems are both complex and advanced, a deep understanding of subject matter,coupled with the ability to transfer such understanding to practical situations can significantly enhance the development of comprehensive skills[12]. Existing research indicates that understanding serves as a cognitive foundation that substantially contributes to skill formation[8].
H1: Understanding has a significant positive effect on university students' skills.

3.3 Metacognition and Skills

Metacognition denotes an individual's awareness, regulation, and reflection on their own cognitive processes, encompassing goal setting, strategy selection, progress monitoring, and self-evaluation[13]. In the educational context of high-level universities, metacognitive ability enables students to plan learning pathways more effectively, optimize the use of resources, and adapt to complex tasks, thereby facilitating improvement in practical skills such as communication, collaboration, and innovation[14].
H2: Metacognition has a significant positive effect on university students' skills.

3.4 Skills and Employability

Skills represent the core observable components of employability, including the application of professional knowledge, organizational coordination, data analysis, teamwork, and innovative practice, among others[15]. Through teaching systems that integrate theory and practice, high-level universities aim to equip students with transferable and applicable composite skills, which directly influence their competitiveness and adaptability in the job market.

H3: Skills have a significant positive effect on university students' employability.

3.5 Self Efficacy and Employability

Self-efficacy refers to an individual's belief in their capability to accomplish specific tasks or respond to challenges. During employment preparation, students with higher self-efficacy tend to set more ambitious career goals, sustain proactive job-search behaviors, and demonstrate greater psychological resilience and adaptability, all of which contribute positively to their overall employability[16].

H4: Self-efficacy has a significant positive effect on university students' employability.

3.6 Theoretical Model Framework

Based on the theoretical and hypothesis analysis presented above, this study proposes the theoretical model illustrated in Figure 1. Grounded in the USEM model, this framework positions understanding (U) and metacognition(M) as antecedent variables of skills(S), and identifies both skills (S) and self-efficacy (E) as direct predictors of employability(E). The model aims to systematically explain the internal mechanisms through which these variables interact. Using partial least squares structural equation modeling (PLS-SEM), this research will perform path analysis and hypothesis testing to clarify the specific influence pathways and relative contributions of understanding, metacognition, skills, and self-efficacy in shaping college students' employability. The findings are expected to provide a theoretical foundation and empirical support for optimizing employability development systems in high-level universities.

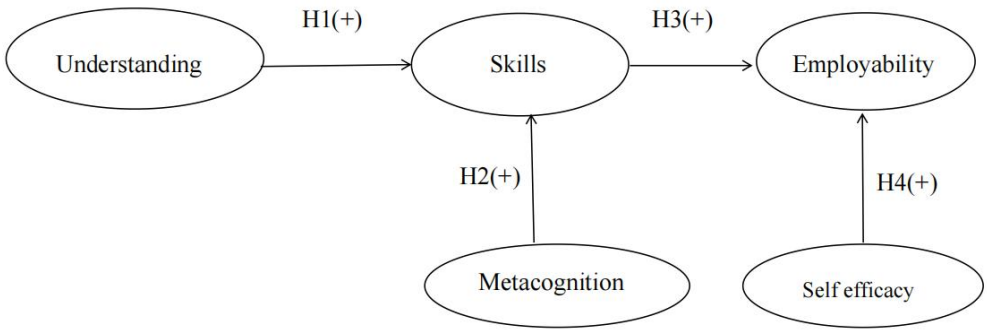

Figure 1 Research Model

4 DATA ANALYSIS

4.1 Descriptive Statistical Analysis

A total of 361 valid questionnaires were collected in this study. As shown in Table 2, among the respondents, 67.9% were female and 32.1% were male. This reflects the gender distribution pattern in certain university majors, particularly those in liberal arts fields, where female students tend to outnumber males. In terms of grade distribution, the sample was predominantly composed of senior students, with juniors and seniors together accounting for 62.3% of the total. Since senior students are at a critical stage of seeking employment or contemplating future career paths, their perceptions and needs regarding employability are more immediate and pronounced. This suggests that the sample well represents students at the employment preparation stage. Regarding major distribution, management (27.1%), economics (24.9%), and literature (21.9%) were predominant, while practical disciplines such as science, engineering, agriculture, and medicine accounted for a relatively lower proportion. This indicates that the sample is characterized by a strong representation of liberal arts and management majors. In terms of teaching methods, nearly half of the students (49.3%) believed that current instruction is primarily theoretical. In contrast, the most favored approach of combination of theory and practice was received by only 37.4% of the students. This suggests a possible imbalance in current teaching practices, with an emphasis on theory over practical application. This is highly relevant to the research topic of employability, as practical skills constitute a core component of employability. With respect to future career directions, more than half of the students (52.4%) chose company employee as their intended career path, making it the most

common choice. This was followed by pursuing a master's degree (24.7%) and becoming a civil servant (17.7%). The proportion of students opting for self-employment was very low (3.6%), which may be related to factors such as risk aversion, limited entrepreneurship education, and insufficient institutional support for start-ups.

Table 2 Descriptive Analysis

Characteristics	Valid	Frequency (n =361)	Percent（%）
Gender	Male	116	32.1
	female	245	67.9
Grade	Freshman	74	20.5
	Sophomore	62	17.2
	Junior	96	26.6
	Senior	129	35.7
Major	Philosophy	1	0.3
	Law	5	1.4
	Literature	79	21.9
	Science	11	3.0
	Engineering	42	11.6
	Agriculture	6	1.7
	Medicine	10	2.8
	Economics	90	24.9
	Pedagogy	3	0.8
	History	2	0.6
	Management	98	27.1
	Arts	14	3.9
Teaching Method	theoretical teaching	178	49.3
	practical teaching	48	13.3
	Theory and practice are equally divided	135	37.4
Future Direction	Master Degree Candidate	89	24.7
	Civil Servant	64	17.7
	Company Employee	189	52.4
	Self-Employment	13	3.6
	Others	6	1.7

4.2 Reliability and Validity

Before conducting the analysis using Partial Least Squares Structural Equation Modeling (PLS-SEM), it is essential to assess the reliability and validity of the measurement tools for each latent variable to ensure the scale exhibits satisfactory internal consistency and convergent validity. The results are presented in Table 3. The Cronbach's Alpha (α) values for all constructs exceed 0.9 (ranging from 0.916 to 0.939), well above the accepted threshold of 0.7, indicating very good internal consistency of the scale[17]. In terms of composite reliability, both rho_a and rho_c values are above 0.9 (ranging from 0.916 to 0.953), substantially exceeding the 0.7 benchmark. This further confirms that the items within each dimension are highly correlated, demonstrating excellent reliability. Regarding convergent validity, all constructs show Average Variance Extracted (AVE) values greater than 0.7 (ranging from 0.748 to 0.804), significantly surpassing the 0.5 criterion[17]. This indicates that each latent variable effectively captures most of the variance in its corresponding items, reflecting strong convergent validity.In summary, the scale used in this study meets all necessary reliability and validity standards for PLS-SEM analysis and is suitable for subsequent model testing.

Table 3 Construct Reliability and Validity

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Employability	0.916	0.916	0.937	0.748
Metacognition	0.925	0.926	0.943	0.768
Self efficacy	0.920	0.923	0.940	0.757
Skills	0.916	0.916	0.937	0.748
Understanding	0.939	0.939	0.953	0.804

4.3 Model Fit

Table 4 Model Fit

Indicator	Saturated model	Estimated model
SRMR	0.042	0.049
d_ULS	0.584	0.790
d_G	0.483	0.522
Chi-square	1037.836	1068.980

NFI	0.886	0.883

To further evaluate the fit between the structural equation model based on the USEM model and the sample data, this study used Smart PLS software to assess model fit. The results are presented in Table 4. Regarding the main fit indices, the standardized root mean square residual (SRMR) value is 0.049, which is below the commonly accepted threshold of 0.08, indicating small overall residuals and a good model fit[18]. Both d_ULS (0.584) and d_G (0.483) also fall within acceptable ranges, further supporting the adequacy of the measurement and structural models in representing the observed data.In addition, the normed fit index (NFI) is 0.886, approaching the recommended standard of 0.90 for excellent fit[18]. This suggests that the model exhibits considerable explanatory power and structural rationality, and is able to reasonably represent the relational structure among the variables.

4.4 Path Analysis and Hypothesis Testing

Given the satisfactory model fit, this study further estimated the structural paths to examine the effects of latent variables on university students' employability. The path coefficients, t-values, and p-values obtained through PLS-SEM analysis are presented in Table 5.

Table 5 Path Analysis and Hypothesis Testing

Hypothesis	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values	Supported
H1:Understanding -> Skills	0.468	0.468	0.065	7.206	0.000	Yes
H2:Metacognition -> Skills	0.435	0.436	0.066	6.564	0.000	Yes
H3:Skills -> Employability	0.470	0.469	0.071	6.658	0.000	Yes
H4:Self efficacy -> Employability	0.391	0.394	0.076	5.164	0.000	Yes

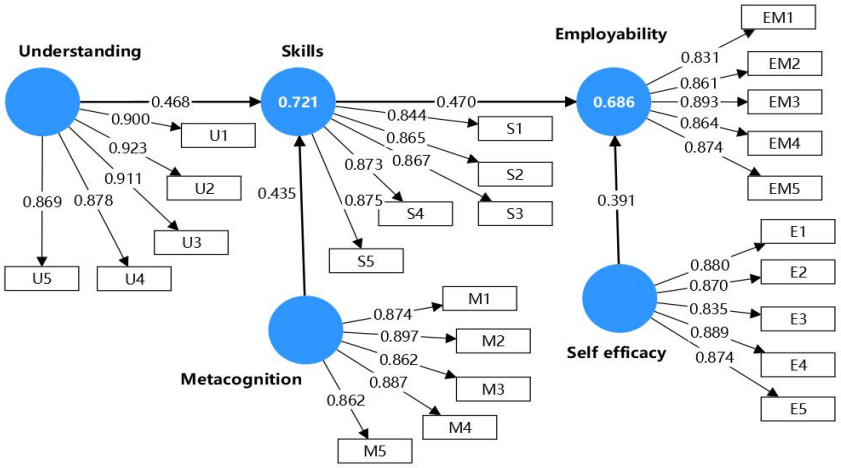

Figure 2 Structural Model with Path Coefficients

Based on the path analysis results shown in Table 5 and Figure 2, H1 and H2 are supported: both Understanding and Metacognition have a significant positive impact on Skills ($\beta_1 = 0.468$, $p < 0.001$; $\beta_2 = 0.435$, $p < 0.001$). This suggests that students' ability to comprehend new knowledge and their capacity to monitor and regulate their own thinking processes serve as important foundations for developing professional skills. Similarly, H3 and H4 are also supported: Skills and Self-efficacy show significant positive effects on Employability ($\beta_3 = 0.470$, $p < 0.001$; $\beta_4 = 0.391$, $p < 0.001$). This indicates that both the specific skills acquired by students and their confidence in performing tasks effectively are core components of employment competitiveness. All path coefficients (Original Sample) range between 0.39 and 0.47, indicating moderate to strong effect sizes. These values suggest that the relationships are not only statistically significant but also practically meaningful. All T-statistics exceed the critical value of 1.96 (at $p < 0.05$), and p-values are all 0.000, confirming that the paths are highly significant. The results fully support the theoretical framework of the USEM model. The model clearly illustrates the mechanism through which employability is formed: deep cognitive abilities（Understanding and Metacognition）jointly enhance Skills, which together with Self-efficacy directly improve Employability. In conclusion, the constructed model demonstrates strong explanatory power and provides empirical support and a theoretical basis for enhancing students' employability by strengthening their cognitive foundations, professional skills, and self-confidence.

5 CONCLUSIONS AND IMPLICATIONS

5.1 Research Conclusions

This study employs the USEM model as its theoretical framework, focusing on four core dimensions (understanding, skills, self-efficacy, and metacognition) to investigate the employability of students from high-level universities in Guangdong Province. Based on 361 valid questionnaire responses and using partial least squares structural equation modeling (PLS-SEM), the mechanisms through which these variables influence employability were systematically examined. The main findings are as follows: First, the model demonstrates a good overall fit. The SRMR value of 0.042 is below the threshold of 0.08, and the NFI value of 0.886 is close to the excellence benchmark of 0.90. These results indicate that the model fits the sample data well, confirming that the USEM model is suitable for explaining the structure of employability among students in high-level universities. Secondly, path analysis reveals that skills and self-efficacy exert significant direct positive effects on employability. Among these, skills ($\beta = 0.470$, $p < 0.001$) are the strongest predictor, suggesting that students' accumulation of professional knowledge, applied skills, and comprehensive competencies constitutes their core advantage in the competitive job market. Self-efficacy ($\beta=0.391$, $p < 0.001$) also shows a significant positive effect, indicating that individuals' confidence in their own abilities and their psychological preparedness during job seeking play essential roles in securing employment. On the other hand, while understanding and metacognition do not exhibit a direct significant impact on employability, both exert important indirect effects mediated through skills. The path coefficient from understanding to skills is 0.468 ($p < 0.001$), and from metacognition to skills is 0.435 ($p < 0.001$). This implies that although higher-order cognitive abilities do not directly enhance employability, they form a crucial foundation for acquiring and developing practical skills. These findings suggest that current employers may prioritize tangible capabilities, being able to get things done over cognitive potential such as strong thinking skills. They also reflect a possible bias in employment-oriented education within universities that emphasizes practical training at the expense of cognitive development.

In summary, this study not only validates the explanatory power of the USEM model in the Chinese context but also elucidates the multi-path formation mechanism of employability among students in high-level Guangdong universities: understanding and metacognition serve as underlying cognitive frameworks that facilitate skill development, while skills and self-efficacy act as direct drivers that collectively enhance employability. It is recommended that universities strengthen both practical skill training and the cultivation of metacognitive and comprehensive abilities to improve students' long-term adaptive capacity, thereby promoting sustainable development of their employability in a more systematic and holistic manner.

5.2 Suggestions for the Construction of High-Level University Groups

Based on the empirical findings regarding the factors influencing employability among students in Guangdong's high-level universities, the following recommendations are proposed to enhance students' employment competitiveness and adaptability:

5.2.1 Enhance practical teaching and emphasize the central role of skills

Empirical results indicate that skills ($\beta = 0.470$) exert the most significant impact on employability. Universities should further increase the weight of practical instruction and improve the "theory-practice integrated" curriculum system. Through project-based learning, industry-academia collaboration, and interdisciplinary hands-on projects, students' comprehensive application abilities and technical operational skills can be strengthened in real-world contexts, thereby effectively boosting their core employment competitiveness[19].

5.2.2 Implement systematic self-efficacy enhancement programs to support students' psychological career readiness

Given the significant positive influence of self-efficacy ($\beta = 0.391$) on employability, universities should establish structured and modular systems for career education and psychological counseling. Activities such as mock interviews, career planning workshops, and resilience training can help students build positive self-perception and career confidence, improving their psychological adaptability and resilience in complex employment environments.

5.2.3 Recognize the foundational supporting roles of understanding and metacognition, and improve mechanisms for cultivating cognitive abilities

Although understanding and metacognition do not directly affect employability, both exert meaningful indirect effects (path coefficients: 0.468 and 0.435, respectively). It is recommended to integrate critical thinking, metacognitive strategy training, and deep learning guidance into specialized courses to help students improve knowledge integration and self-regulation capabilities, providing sustained momentum for long-term career development.

5.2.4 Promote targeted employment guidance and adopt differentiated support strategies for various student groups

Universities should utilize data analysis to provide tailored guidance based on students' majors, grade levels, and career aspirations. Emphasis should be placed on precision and customization in resource allocation and service design. For instance, liberal arts students may benefit from enhanced practical skill training, while science and engineering students could receive more training in communication and collaborative skills. Such strategies will help optimize employment support services and strengthen the leading role of high-level universities within the regional talent supply structure.

Through these measures, a four-dimensional framework for employability development—"skills empowerment, psychological reinforcement, cognitive support, and precision services"—can be established, holistically improving the employability and social adaptability of students in high-level universities.

COMPETING INTERESTS

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A DEEP LEARNING DRIVEN ANALYSIS OF THE NON-LINEAR AND INTERACTIVE EFFECTS OF TITLE EMOTION AND VIDEO LENGTH ON DEPTH OF COMMUNICATION IN BILIBILI

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Abstract: In the competitive digital landscape of online video platforms, understanding the drivers of user engagement is paramount for content creators and platform strategists. This study investigates the complex, non-linear relationships between video title sentiment intensity, video duration, and user engagement, measured by like counts, within the automotive content niche on the Chinese platform Bilibili. Drawing on a dataset of 892 videos collected via web scraping, this research employs a multi-method analytical approach, combining OLS regression with advanced techniques including quantile regression and SHAP analysis based on an XGBoost model. The findings reveal that both title sentiment intensity and video duration have significant, non-linear (U-shaped and quadratic, respectively) effects on the natural logarithm of like counts. Specifically, videos with either very low (neutral) or very high (emotional) title sentiment intensity tend to receive more likes than those with moderate intensity. Furthermore, a significant interaction effect is uncovered, with the Johnson-Neyman analysis indicating that the effect of sentiment intensity is significantly moderated by video duration. Quantile regression results show that these effects are heterogeneous across different levels of video popularity, suggesting that the drivers of engagement for viral content differ from those for average videos. While the overall model explains a modest portion of the variance, the identified non-linear and interactive patterns challenge simplistic linear assumptions and provide nuanced, actionable insights. The study contributes to the field of computational communication by demonstrating a sophisticated analytical framework for dissecting engagement metrics and offers practical guidance for content strategy in vertical interest communities.
Keywords: User engagement; Sentiment intensity; Video duration; Bilibili; Computational communication; Non-linear effects; Interaction effects; SHAP

1 INTRODUCTION

The proliferation of online video platforms has fundamentally reshaped information dissemination and user interaction, establishing itself as a core battleground for audience attention [1]. Platforms such as YouTube, TikTok, and Bilibili have evolved into complex ecosystems where billions of users consume, create, and engage with content, making user engagement a critical currency for creators, marketers, and the platforms themselves. Engagement, often operationalized through metrics like views, likes, comments, and shares, not only signifies audience appreciation but also directly influences content visibility through algorithmic amplification [2]. Consequently, identifying the determinants of user engagement has become a central pursuit in digital communication research.

This study focuses on Bilibili, a unique and influential platform in the Chinese digital media landscape. Unlike its global counterparts, Bilibili has cultivated a distinct community culture, primarily centered around its "Generation Z" user base [3]. Several characteristics make Bilibili a compelling context for this research. First is its signature "Danmu" (or "bullet comments") system, where real-time user comments float across the screen, fostering a sense of co-viewing and collective experience that enhances participation [4]. Second, the platform's ecosystem is highly dependent on the relationship between content creators, known as "UPzhu" (literally "uploader"), and their fans, creating strong community ties and high user stickiness [5]. Finally, Bilibili hosts a vast array of deep, vertical-interest content, moving beyond general entertainment to specialized fields. The automotive niche, in particular, represents a highly competitive and valuable market where creators produce in-depth reviews, test drives, and technical analyses, demanding sophisticated content strategies to capture audience engagement [6].

Within this context, content creators face strategic dilemmas regarding content production and presentation. Two of the most fundamental and controllable elements are the video's duration and its title. Video length is a constant balancing act between providing substantive content and retaining audience attention in an era of declining attention spans [7]. Video titles, as the primary textual gateway to the content, serve to manage expectations, convey information, and evoke emotion to entice clicks and engagement. The emotional tone, or sentiment, of a title is a powerful tool in this regard [8].

While a body of literature has explored the effects of sentiment and content length on user engagement, research has often relied on linear models and has underexplored the nuanced, potentially non-linear and interactive relationships between these variables. It is plausible, for instance, that the effect of a highly emotional title is not uniform but depends on the length of the video it represents—a long-form documentary may benefit from a different titling strategy than a short, punchy clip. Moreover, the nature of sentiment itself is complex; much research has focused on valence (positive vs.

negative), while the impact of emotional intensity (arousal) is less understood. A neutral, objective title and a highly emotional one may be more effective than a mildly emotional one, suggesting a U-shaped or curvilinear relationship [9].

To address these gaps, this study undertakes a deep computational analysis of 892 automotive videos from Bilibili. It moves beyond traditional linear assumptions to investigate the following research questions:

RQ1: What are the individual effects of video duration and title sentiment intensity on user engagement (measured by like counts)?

RQ2: Are the relationships between video duration, title sentiment intensity, and user engagement non-linear?

RQ3: Does video duration moderate the relationship between title sentiment intensity and user engagement?

To answer these questions, this study employs a multi-faceted analytical approach. We begin with descriptive and bivariate analyses, followed by a hierarchical OLS(ordinary least squares) regression to model the main, non-linear, and interactive effects. We then probe the significant interaction using the Johnson-Neyman technique. To further enhance the robustness and depth of our findings, we utilize quantile regression to explore how these effects vary across different levels of video popularity and employ SHAP (SHapley Additive exPlanations) on a trained XGBoost model to provide machine learning-based insights into feature importance and interactions [10].

This research aims to make several contributions. Theoretically, it challenges simplistic linear models of user engagement and provides empirical evidence for the complex, curvilinear, and interactive nature of content characteristics' effects. Methodologically, it showcases a comprehensive workflow combining traditional statistical inference with advanced computational techniques to yield a more holistic understanding. Practically, the findings offer nuanced, data-driven insights for content creators in the automotive niche and beyond, helping them optimize their titling and content length strategies to maximize user engagement on platforms like Bilibili.

2 LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

2.1 User Engagement on Digital Media Platforms

User engagement is a cornerstone concept in digital communication, broadly defined as the cognitive, affective, and behavioral investment a user makes in their interactions with a media object or platform [11]. In the context of social video platforms, engagement is typically operationalized through a suite of observable behavioral metrics, including views, likes, comments, and shares [12]. While views may indicate reach, "thicker" engagement metrics like likes and comments are often interpreted as more active forms of audience feedback and approval [13]. Likes, in particular, serve as a low-cost, immediate signal of positive reception, and their aggregation functions as a powerful social proof heuristic that can influence subsequent viewers' perceptions and engagement [14]. Furthermore, these engagement signals are critical inputs for platform recommendation algorithms, which prioritize and promote content that demonstrates a high potential for user interaction, creating a feedback loop where engagement begets visibility [15].

2.2 The Role of Content Characteristics: Duration and Titling

The effect of video duration on engagement is complex and contested. Some research suggests that in an economy of attention, shorter content is more effective, capturing users before their attention wanes [16]. This is exemplified by the rise of short-form video platforms like TikTok. However, other studies find a positive relationship between video length and certain engagement outcomes, particularly on platforms like YouTube that reward watch time [17]. Longer videos may afford creators the opportunity to build a more compelling narrative, provide more in-depth information, and foster a stronger parasocial relationship with the viewer, leading to higher overall satisfaction and engagement. This suggests that the optimal video length is likely context- and platform-dependent. In this study, we hypothesize a positive but potentially non-linear relationship, where engagement increases with duration up to a certain point before plateauing or declining as videos become excessively long [18]. This is reflected in our decision to test for a quadratic effect of duration.

As the primary textual cue, the video title is instrumental in setting expectations and driving click-through behavior [12]. The emotional content of text, or sentiment, has been shown to be a potent driver of information diffusion and engagement. Research on textual sentiment often focuses on valence (the positivity or negativity of the emotion). Studies have found evidence for both a "positivity bias," where positive content is shared more widely, and a "negativity bias," where negative content can be more arousing and attract more attention [8].

However, a focus solely on valence may overlook the role of emotional arousal or intensity—the degree of emotional activation a piece of content evokes, regardless of its positive or negative direction. High-arousal emotions (e.g., awe, anger, anxiety) have been found to be more viral than low-arousal emotions (e.g., sadness, contentment) [19]. This study operationalizes sentiment in terms of intensity, arguing that in the crowded attention market of video platforms, the primary function of a title's emotion is to be arresting and arousing. We hypothesize a non-linear, U-shaped relationship between sentiment intensity and engagement. Titles with very low intensity may succeed by appearing objective, informative, and professional, while titles with very high intensity may succeed by being emotionally provocative and acting as effective "clickbait." Titles with moderate, lukewarm emotionality may fail to stand out, thus receiving lower engagement. This is represented by our first hypothesis:

H1: The relationship between title sentiment intensity and like counts will be non-linear (U-shaped).

2.3 Interaction Effects and a Moderated Model

The effects of individual content characteristics do not operate in a vacuum. It is crucial to consider how they interact to jointly influence user engagement. The effectiveness of a particular titling strategy, for example, may be contingent on the nature of the content it represents. An intensely emotional title might seem appropriate for a short, dramatic clip but could feel mismatched or exhausting for a 30-minute technical deep-dive. Conversely, the investment required to watch a long video might be better justified by a title that promises high informational value (low sentiment intensity) or high emotional payoff (high sentiment intensity).

This leads to the concept of moderation, where the relationship between a predictor (sentiment intensity) and an outcome (like counts) is altered by the level of a third variable (video duration). We propose that video duration moderates the effect of sentiment intensity on engagement. This aligns with a contingency perspective on media effects, suggesting that there is no single "best" content strategy, but rather that optimal strategies depend on the interplay of multiple factors. Therefore, we posit our second hypothesis:

H2: Video duration will moderate the relationship between title sentiment intensity and like counts.

By testing these hypotheses, this study aims to provide a more nuanced and comprehensive model of user engagement, accounting for the non-linear and interactive ways in which content characteristics shape audience behavior in a modern digital media environment.

3 METHODS

3.1 Data Collection and Sample

The data for this study were collected from Bilibili (bilibili.com), a prominent video-sharing platform in China. A dataset was compiled by executing a custom web scraper using Python, targeting videos within the automotive content category. The data collection period spanned from July 2019 to December 31, 2024, to ensure a wide representation of videos over time.

The initial sample consisted of videos primarily focused on automotive topics, including vehicle reviews, test drive experiences, model comparisons, and brand events. A data cleaning process was then implemented to ensure data quality. Videos were excluded if they had poor image quality, lacked essential information about the vehicle or presenter, or had audio-video synchronization issues. After this filtering process, the final sample consisted of N = 892 unique videos. The sample includes content from creators of varying sizes and audience levels, enhancing the generalizability of the findings within the Bilibili automotive community.

3.2 Measures

3.2.1 Dependent variable

User engagement was operationalized as the total number of "likes" a video received. The raw distribution of like counts was found to be heavily right-skewed, a common characteristic of engagement metrics where a small number of videos achieve viral popularity. This positive skewness violates the assumptions of ordinary least squares (OLS) regression. As shown in Figure 1 the mean like count (31,614) was substantially higher than the median (19,507), confirming the presence of high-value outliers. To normalize the distribution, a natural logarithm transformation was applied to the like count variable (ln(Like Count + 1) to handle any cases of zero likes). The resulting log-transformed variable, Log_Like_Count, was approximately normally distributed (Mean = 9.88, Median = 9.88, Skewness = 0.10) and served as the dependent variable in all regression analyses.

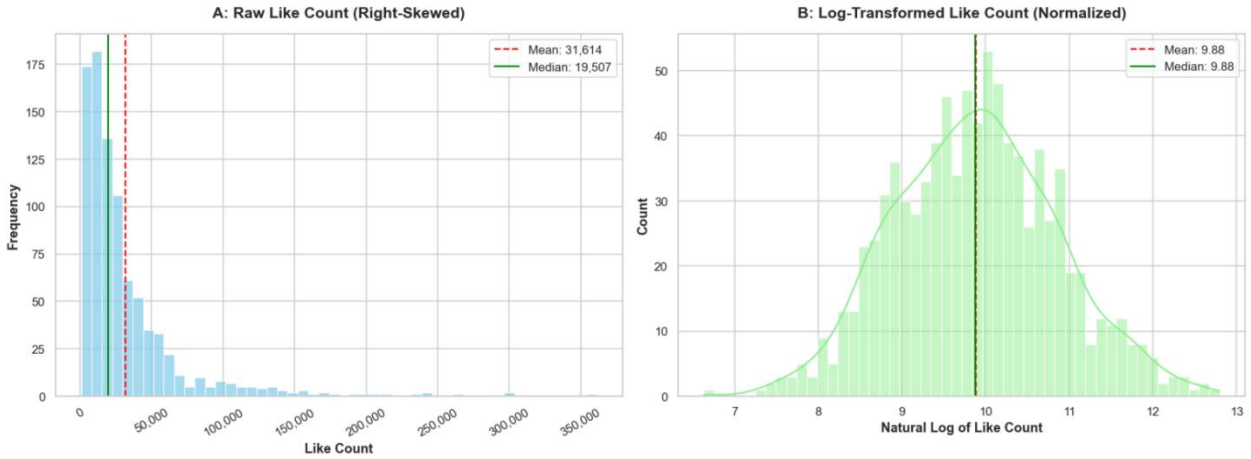

Figure 1 Like Count Distribution Before and After Log Transformation: (A) the raw, right-skewed distribution of like counts, and (B) the normalized, bell-shaped distribution after log transformation

3.2.2 Independent variables

Video Duration. This was measured in total seconds, from the start to the end of the video. The duration of videos in the sample ranged from 26 seconds to 1,436 seconds, with a mean of 649.57 seconds (approx. 10.8 minutes). The distribution of video duration was slightly right-skewed, as depicted in Figure 2.

Title Sentiment Intensity. This key variable was derived through a two-step process to measure the degree of emotional arousal in a video's Chinese title. First, a pre-trained multilingual BERT (Bidirectional Encoder Representations from Transformers) sentiment classification model was employed. This model, trained on a five-star rating system, analyzed each video title to produce a raw sentiment valence score (Sraw) on a continuous scale from [0, 1], where 0 represented the most negative sentiment, 1 represented the most positive sentiment, and 0.5 represented neutrality. Second, to capture emotional intensity irrespective of valence, the raw valence score was transformed using the following formula: Sintensity = 2 × |Sraw - 0.5|. This calculation converts the U-shaped valence scale into a linear intensity scale. Scores near the neutral midpoint of 0.5 on the valence scale result in an intensity score near 0 (low arousal), while scores at the extremes (near 0 or 1) result in an intensity score near 1 (high arousal). This final Sintensity score was used in the analysis.

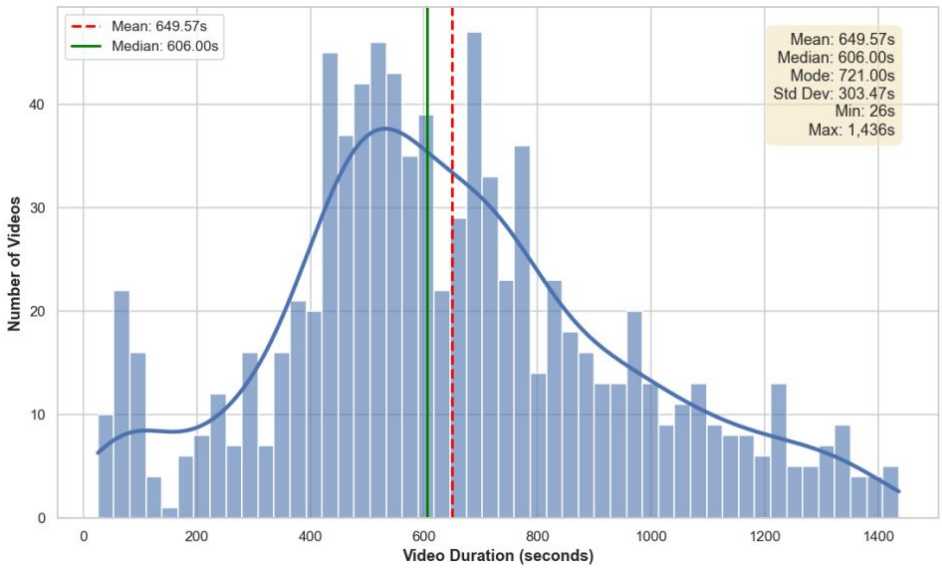

Figure 2 Distribution of Video Duration

3.3 Analytical Strategy

The data analysis was conducted in several stages. First, descriptive and bivariate analyses were conducted. The initial bivariate relationship between video duration and Log_Like_Count was assessed using a Pearson correlation coefficient, visualized in Figure 3. Videos were then grouped into bins based on duration and sentiment intensity to visualize average like counts, as shown in Figure 4, Figure 5 and Figure 6. Further visualizations, including a hexbin density plot (see Figure 7) and a binned heatmap (see Figure 8), were used to explore the joint distribution of the independent variables.

Second, to formally test the hypotheses, a hierarchical OLS regression analysis was performed. The final model (Model D) included main effects, quadratic terms to test for non-linear relationships (H1), and an interaction term to test for moderation (H2), as visualized in Figure 9. Model diagnostics were performed (see Figure 10). Third, a significant interaction was probed using the Johnson-Neyman technique (see Figure 11). Finally, advanced supplementary analyses, including quantile regression (see Figure 12) and SHAP analysis on an XGBoost model (see Figure 13 and Figure 14), were used to add depth and robustness.

4 RESULTS

4.1 Descriptive and Preliminary Analyses

Preliminary analysis revealed a weak but statistically significant positive linear correlation between video duration and the log-transformed like count ($r = .071$, $p = .035$), as shown in Figure 3. This suggests that, overall, longer videos tend to garner slightly more likes.

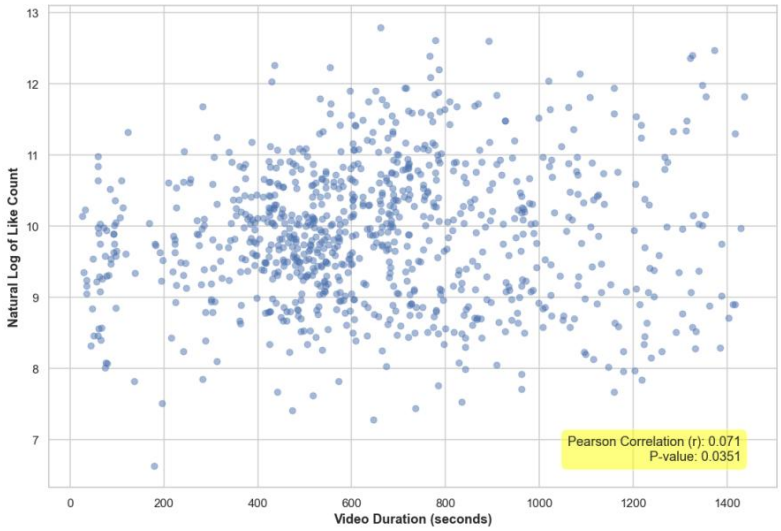

Figure 3 Relationship between Video Duration and Log-Transformed Like Count

A more detailed examination using binned analysis provided richer insights. As shown in Figure 4, there is a clear monotonic trend of increasing average like counts as video duration increases. Videos shorter than 1 minute had the lowest average likes (11,458), while those longer than 20 minutes had the highest (43,281). However, when considering engagement efficiency, this trend reverses. Figure 5 demonstrates that shorter videos are far more efficient at accumulating likes per minute. "Shorts" (< 1 min) averaged 19,618 likes per minute, a figure that drops sharply to 1,978 for videos over 20 minutes long.

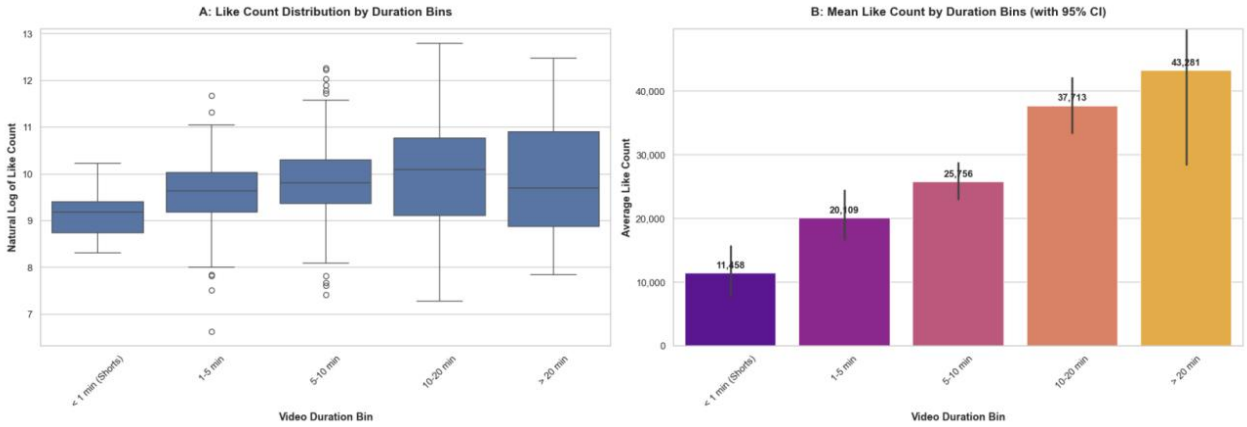

Figure 4 Like Count Analysis by Binned Video Duration

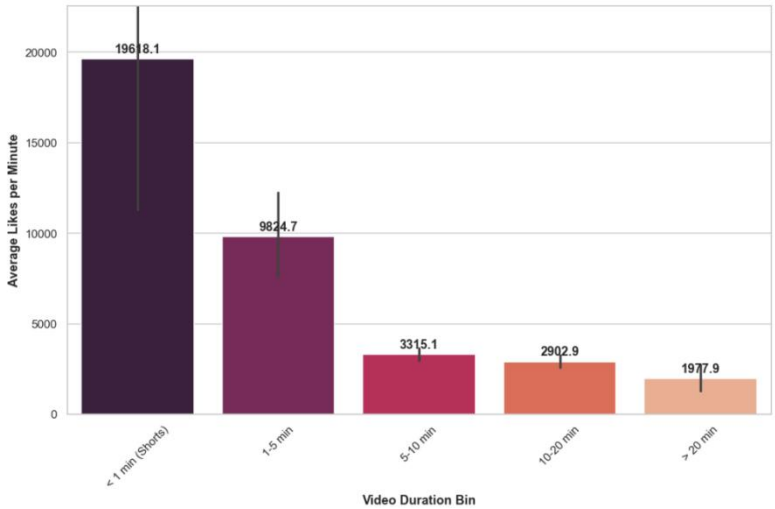

Figure 5 Like Efficiency by Video Duration

The analysis of sentiment intensity bins (see Figure 6) revealed a non-linear pattern. Average like counts were highest at the extremes: 34,351 for the "Very Low" intensity bin (0-0.2) and 41,026 for the "Very High" intensity bin (0.8-1.0), providing initial support for the U-shaped hypothesis (H1). However, a one-way ANOVA indicated these differences were not statistically significant, $F(4, 887) = 1.53$, $p = .192$.

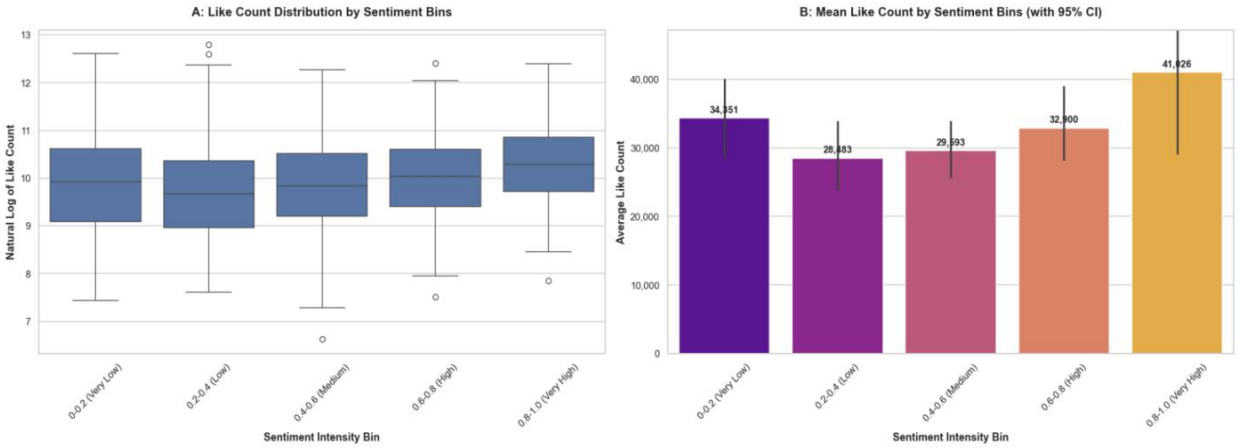

Figure 6 Like Count Analysis by Binned Sentiment Intensity

To visually explore the joint relationship and potential interaction between the independent variables, a hexbin density plot and a binned heatmap were generated. The hexbin plot (Figure 7) maps the joint distribution of sentiment intensity and video duration, with color indicating the mean log-transformed like count. It reveals that the highest concentrations of engagement (brighter colors) are most frequently observed for videos with a moderate duration (approximately 200-800 seconds) and a moderate-to-high sentiment score (approximately 0.4-0.7), suggesting a complex, non-linear relationship rather than a simple trend toward the extremes.

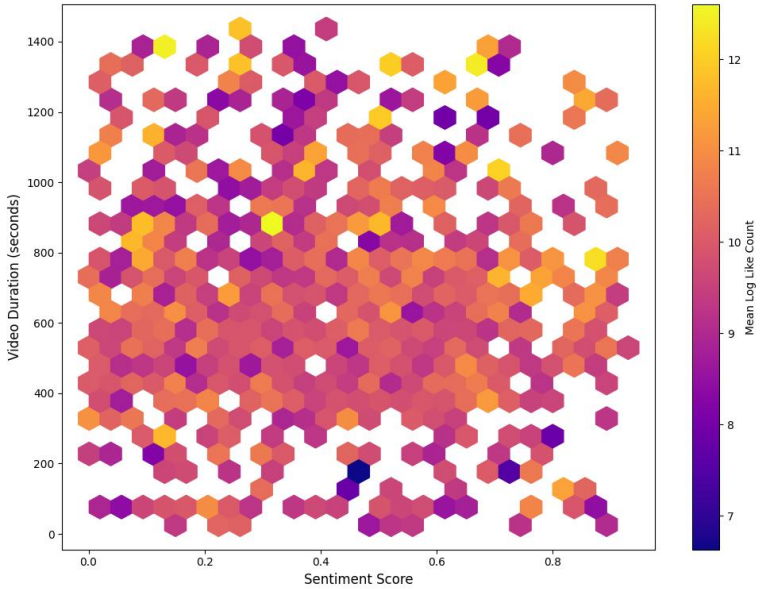

Figure 7 Hexbin Density Plot

To clarify this interaction with raw engagement numbers, the binned heatmap (Figure 8) displays the average actual like count for discrete bins of both variables. This visualization powerfully illustrates a non-monotonic interaction pattern, showing that the effect of sentiment intensity is highly conditional on video length. For instance, the single highest-performing combination was for videos longer than 20 minutes with a high sentiment score (0.6-0.8), garnering an average of approximately 65,910 likes. In stark contrast, the same high sentiment score in the shortest videos (< 3 minutes) resulted in one of the lowest outcomes, with only 12,698 average likes. This strong visual evidence that the effectiveness of a titling strategy depends fundamentally on video duration motivates the formal moderation analysis in the subsequent regression model.

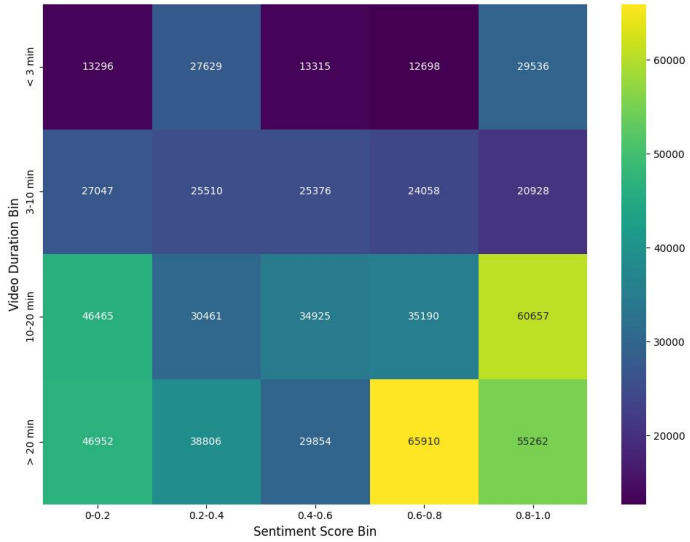

Figure 8 Binned Heatmap (Actual Mean Like Count)

4.2 Hierarchical Regression Analysis

A hierarchical OLS regression was performed to formally test the hypotheses. The final model (Model D) provided the best fit, with an Adjusted R^2 of .033. While modest, this indicates the model explains approximately 3.3% of the variance in log-transformed like counts. Diagnostic checks (Figure 9) confirmed the model assumptions were reasonably met.

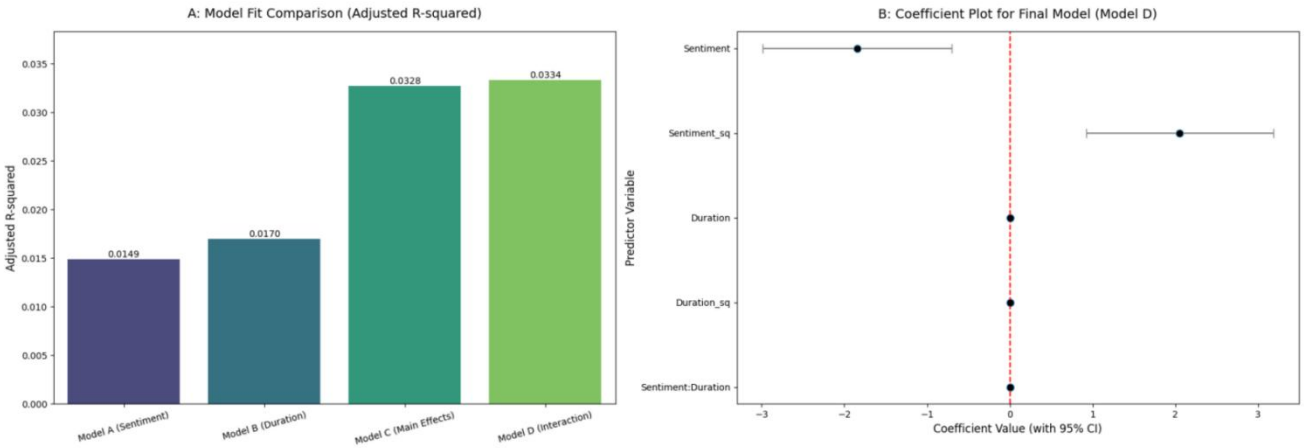

Figure 9 Hierarchical Regression Results

The coefficients for the final model (see Figure 9) revealed significant findings. The coefficients for 'Sentiment_Intensity'(b = -1.846, p = .002) and 'Sentiment_Intensity²' (b = 2.054, p < .001) were both significant, describing a convex, U-shaped curve and confirming H1. Similarly, the coefficients for 'Duration' (b = 0.0013, p = .002) and 'Duration²' (b ≈ -0.0000, p < .001) were significant, describing an inverted U-shape. Crucially, the interaction term 'Sentiment_Intensity' × 'Duration' was statistically significant (b = 0.0006, p < .05), supporting H2.

To ensure the validity of the OLS regression results, a series of model diagnostics were performed, as shown in Figure 10. The Residuals vs. Fitted plot (Panel A) and the Scale-Location plot (Panel C) show that the residuals are randomly scattered around the horizontal line without any obvious patterns, satisfying the assumptions of linearity and homoscedasticity. Furthermore, the Normal Q-Q plot (Panel B) reveals that the residuals closely follow the theoretical diagonal line, indicating that the assumption of normality is meet. While the Cook's Distance plot (Panel D) identifies 51 observations with potential influence (Cook's distance > 4/n), none have a Cook's distance greater than 1, suggesting that no single data point excessively biases the model. Overall, the diagnostic plots confirm that the final regression model (Model D) is robust and its assumptions are well-satisfied.

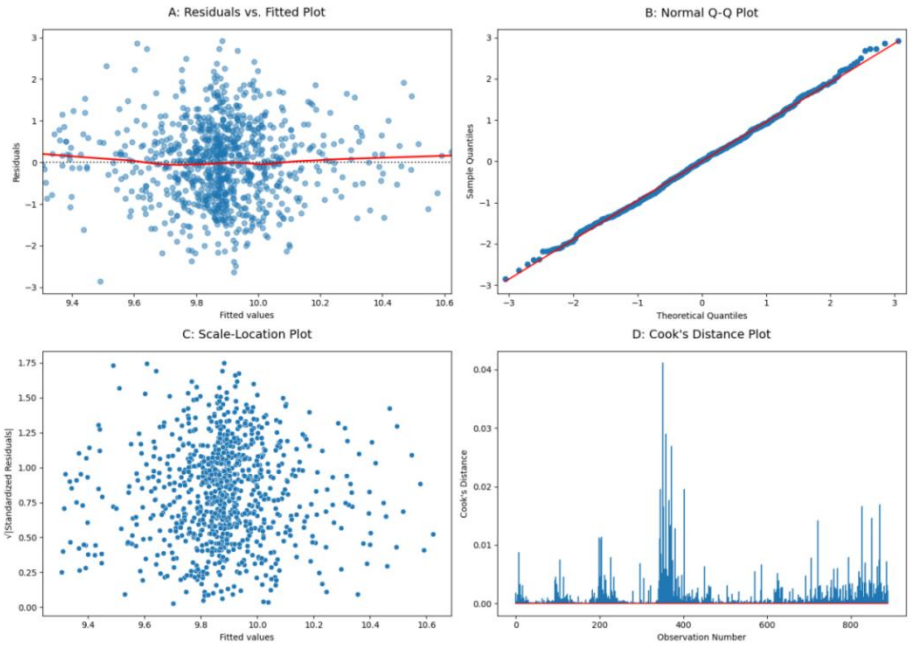

Figure 10 Diagnostic Plots for Final Model (Model D)

4.3 Probing the Interaction: Johnson-Neyman Analysis

The Johnson-Neyman (J-N) analysis was conducted to interpret the significant moderation effect (Figure 11). The analysis revealed that for videos with a duration between 26 seconds and approximately 1,209 seconds (~20 minutes), the marginal effect of sentiment intensity is significantly negative. This indicates that for most videos, as sentiment intensity increases, the predicted like count initially decreases (the downward slope of the U-curve). The positive moderating effect means this negative slope becomes less severe as duration increases. For videos longer than 1,209 seconds, the effect was not significant.

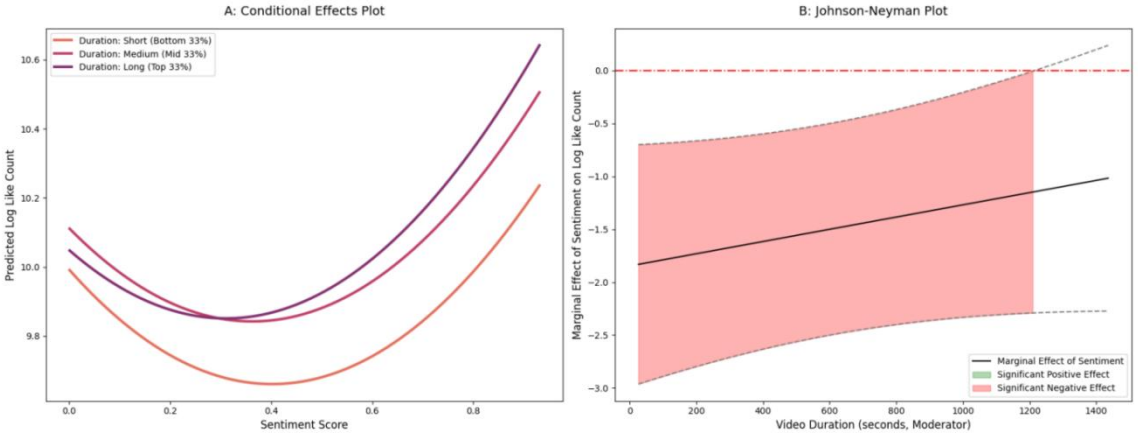

Figure 11 Interaction Visualization and Region of Significance

4.4 Advanced Analyses: Quantile Regression and SHAP

To add depth and robustness to the OLS findings, two advanced analytical techniques employed. First, quantile regression used to investigate whether the interaction effect was consistent across videos with varying levels of popularity. The results, shown in Figure 12, reveal that the effect is highly heterogeneous and not stable across the popularity distribution. For median-performing videos (at the 50th percentile), the interaction coefficient was significantly positive, indicating that for this group, longer duration amplifies the positive impact of extreme sentiment. However, in a striking reversal, the coefficient becomes significantly negative for slightly more popular videos (at the 60th percentile), suggesting that the strategic interplay of sentiment and duration that helps a video achieve average popularity may be different from the strategy needed to push it into a higher tier of engagement.

Second, to complement the statistical inference from OLS, an explainable AI approach used by training a high-performance XGBoost model and interpreting it with SHAP values. The SHAP summary plot (Figure 13) provides a global ranking of feature importance. Consistent with the regression model, it identified Sentiment (mean absolute SHAP value = 0.3654) as the marginally most influential feature in driving predictions, closely followed by Duration (mean absolute SHAP value = 0.3579). The wide horizontal spread of SHAP values for both features visually confirms their

substantial and complex impact. Furthermore, the SHAP interaction dependence plot (Figure 14) directly visualized the synergy between the two variables. It confirmed a slight positive average interaction effect (mean interaction SHAP value $\approx$ 0.0087), corroborating the core moderation hypothesis from a machine learning perspective. More specifically, the plot revealed that this positive synergy is most pronounced for long videos (represented by red points) that also have high-intensity titles, providing convergent evidence for the conditional nature of these effects.

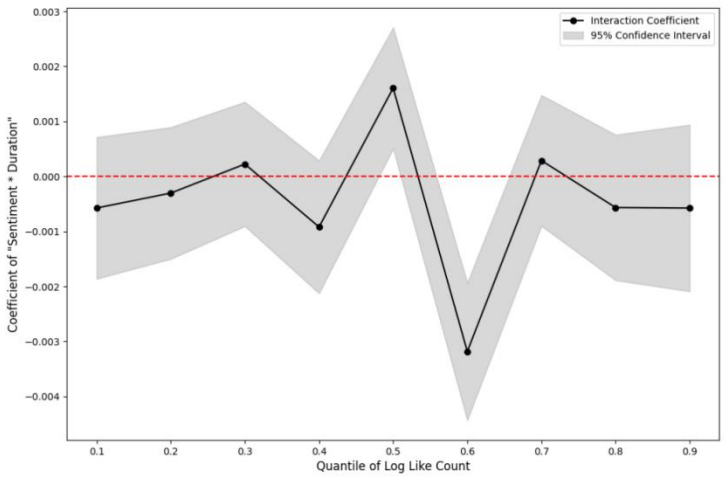

Figure 12 Quantile Regression Coefficients for the Interaction Term

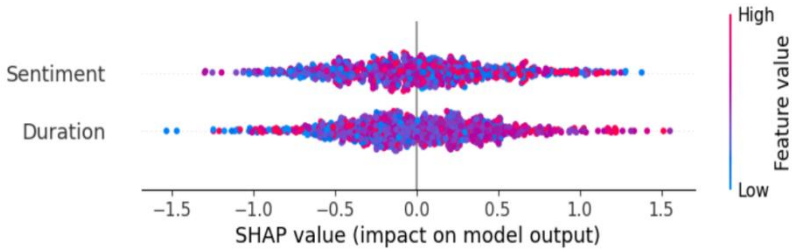

Figure 13 SHAP Summary Plot

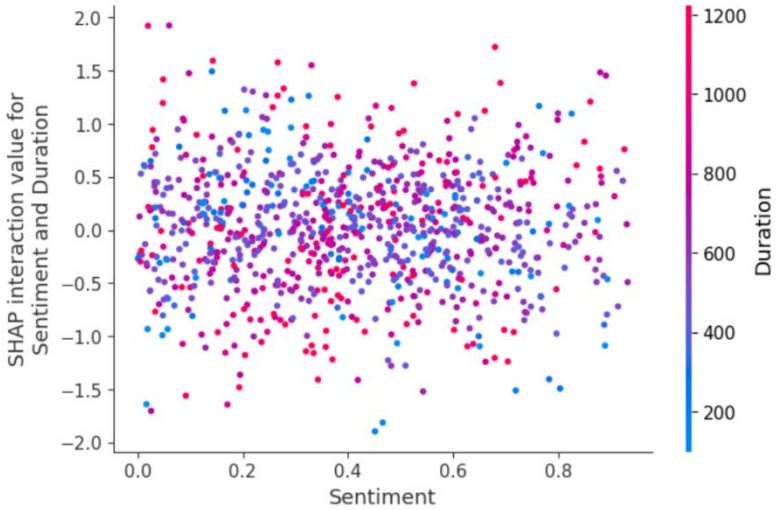

Figure 14 SHAP Interaction Dependence Plot

5 DISSCUSSION

5.1 Summary and Interpretation of Key Findings

This study set out to unravel the complex relationships between video title sentiment intensity, video duration, and user engagement on Bilibili. First, the results robustly demonstrate that the relationships of both title sentiment intensity and video duration with like counts are non-linear. For sentiment intensity, we found a significant U-shaped effect, confirming H1. This suggests that content titling strategies may succeed at the extremes: very low intensity (objective, professional)

and very high intensity (emotionally provocative) titles both perform well, while moderately emotional titles are associated with the lowest engagement.

For video duration, we found a significant, though diminishing, positive effect. Longer videos tend to get more likes, but the returns diminish, indicating a potential ceiling effect. This, combined with the "like efficiency" analysis, presents a strategic choice for creators between maximizing total engagement with longer content and producing efficient, easily digestible shorter content.

Second, and central to this study, is the confirmation of a significant moderation effect (H2). Video duration alters the relationship between sentiment intensity and engagement. The J-N analysis revealed that for the majority of videos (up to ~20 minutes), the dominant effect of increasing sentiment intensity is negative. This implies that for a typical-length video, a more neutral, fact-driven title is a safer strategy than a moderately emotional one. The interaction's positive coefficient indicates that as videos get longer, this negative effect is attenuated, possibly because a longer video provides the necessary space to justify a highly emotional title's claim.

Finally, our advanced analyses revealed the heterogeneity of these effects. Quantile regression showed that the nature of the interaction is not consistent across the popularity spectrum. Furthermore, the SHAP analysis corroborated the findings from the OLS regression, confirming that sentiment intensity and duration are the two most critical features and that they interact in meaningful ways.

5.2 Theoretical and Practical Implications

Theoretically, this study provides strong empirical evidence against the adequacy of simple linear models for studying user engagement, highlighting the necessity of testing for curvilinear and interactive effects. It also refines our understanding of sentiment's role by focusing on 'intensity'(arousal) rather than just 'valence', revealing a U-shaped pattern that suggests a duality of successful communication strategies: one rooted in objectivity and information (low arousal), and another in emotion and provocation (high arousal).

Practically, the implications for content creators are significant. The key takeaway is that there is no one-size-fits-all strategy. First, titling is context-dependent: the choice between a neutral or an emotional title should be made in conjunction with video length. Second, creators must balance total engagement with efficiency, choosing a video length that aligns with their specific goals. Third, for titling, the least effective strategy appears to be moderate emotionality; titles should be either clearly informative or clearly emotional.

5.3 Limitations and Future Research

This study has several limitations. First, the final regression model explained a relatively small portion of the variance in like counts (Adjusted $R^2 \approx .033$), indicating that other variables play a much larger role. Future research should incorporate creator-level variables such as subscriber count. Second, the data is correlational, precluding causal claims; experimental designs would be necessary to establish causality. Third, our findings are specific to the automotive niche on Bilibili and may not be generalizable to other genres or platforms. Finally, our operationalization of sentiment intensity, while an improvement on simple valence, could be further refined by classifying discrete emotions.

6 CONCLUSION

This study demonstrates that the relationship between video content characteristics and user engagement is far more complex than linear models suggest. For automotive videos on Bilibili, the path to engagement is not a straight line but a landscape of shifting curves. Our findings pinpoint a significant U-shaped relationship for title sentiment intensity, revealing that both highly objective (low-intensity) and highly emotional (high-intensity) titles significantly outperform those with moderate emotionality. Similarly, while longer videos tend to accumulate more likes, they do so at a diminishing rate and at a steep cost to engagement efficiency. The central contribution of this research is the identification of a significant interaction effect: the power of an emotional appeal is fundamentally conditional on the temporal commitment a video asks of its audience. Our analysis reveals that for the vast majority of videos in this niche (under approximately 20 minutes), the initial effect of increasing a title's emotional intensity is, counterintuitively, negative. This complex interplay is vividly illustrated by our finding that a high-intensity title paired with a long video (>20 minutes) can yield over five times more likes (averaging ≈65,910) than the exact same titling strategy applied to a short video (<3 minutes), which averaged only ≈12,698 likes. By employing a diverse computational toolkit, from OLS regression to SHAP analysis on an XGBoost model, this research provides a robust, nuanced understanding of these dynamics, offering both theoretical depth for communication scholars and concrete, data-informed heuristics for digital content creators navigating the ever-evolving attention economy.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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