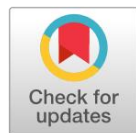


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The Digital Toll: A Cross-Cultural Study on Technostress and Digital Fatigue among K-12 Students during Hybrid Learning

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ABSTRACT

Background. The rapid expansion of hybrid learning has intensified K–12 students' reliance on digital technologies, creating growing concerns regarding technostress, digital fatigue, academic engagement, and school-related well-being across diverse cultural and educational contexts.

Purpose. This study aimed to examine how digital learning demands contribute to technostress and digital fatigue among K–12 students, investigate their academic and psychological consequences, identify potential protective factors, and determine whether these relationships vary across cultural settings.

Method. A cross-cultural quantitative design was employed involving K–12 students participating in hybrid learning environments. Survey data were analyzed using measurement-invariance testing, multilevel analysis, and structural equation modeling to examine relationships among digital learning demands, technostress, digital fatigue, academic engagement, school-related well-being, and protective factors at individual and contextual levels.

Results. The findings showed that technology overload, platform complexity, task fragmentation, connectivity problems, and expectations of continuous availability significantly predicted higher levels of technostress. Increased technostress subsequently intensified digital fatigue and was associated with lower academic engagement and poorer school-related well-being. Digital self-efficacy, teacher support, and adequate recovery opportunities buffered several adverse relationships.

Conclusion. The findings demonstrate that the digital toll of hybrid learning is shaped more strongly by the intensity and organization of digital demands than by screen duration alone. Sustainable hybrid education therefore requires manageable digital workloads, coherent platform ecosystems, responsive teacher support, equitable technological conditions, and meaningful opportunities for recovery.

KEYWORDS

Digital Fatigue, Digital Well-Being, Hybrid Learning

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INTRODUCTION

Digital technologies have become deeply embedded in contemporary K–12 education, transforming how students access learning materials, communicate with

teachers, complete assignments, collaborate with peers, and participate in classroom activities. The expansion of hybrid learning has further integrated digital platforms with face-to-face instruction, creating educational environments in which students continuously move between physical and virtual spaces (Dong dkk., 2026; K. Jia & Sadiq, 2026; H. Zhang dkk., 2026). Learning management systems, videoconferencing applications, educational platforms, digital assessments, and mobile communication tools can increase flexibility and continuity of learning. Their widespread use also raises an important question concerning the cumulative psychological and cognitive demands placed on school-age learners whose developmental needs differ substantially from those of adult technology users.

Hybrid learning is frequently discussed in terms of flexibility, accessibility, personalization, and technological innovation, yet its effectiveness also depends on the quality of students' everyday digital experiences (Cepeda-Cardona & Arias-Pérez, 2025; L. Chen dkk., 2026; Chong dkk., 2025). Continuous notifications, multiple learning platforms, frequent online assignments, prolonged visual attention, information overload, technical interruptions, and expectations of constant connectivity may create pressures that extend beyond ordinary academic demands. Students may experience difficulty concentrating, mental exhaustion, frustration, reduced motivation, physical discomfort, or a sense of being overwhelmed by persistent technology-mediated learning. These experiences suggest that educational digitalization has potential costs that require systematic investigation alongside its recognized benefits.

Technostress and digital fatigue provide two important conceptual lenses for understanding these costs. Technostress refers to psychological strain arising when technological demands exceed an individual's perceived capacity or resources to manage them effectively, while digital fatigue describes cognitive, emotional, and physical exhaustion associated with sustained digital engagement. These phenomena are related but should not be treated as identical (LEI & Ngai, 2026; C. Liu & Sun, 2026; Mikkonen dkk., 2026). Technostress emphasizes the imbalance between technological demands and coping resources, whereas digital fatigue represents a possible cumulative outcome of prolonged and demanding digital interaction. Examining their relationship can provide a more nuanced understanding of the "digital toll" experienced by students in hybrid education.

The first major problem concerns the assumption that increased exposure to digital learning technologies produces relatively similar effects across students. K–12 learners differ substantially in age, developmental stage, digital competence, self-regulation, learning autonomy, family support, socioeconomic resources, and access to appropriate devices (S. Chen dkk., 2026; Khalequzzaman dkk., 2025; C.-F. Liu dkk., 2026). The same digital workload may therefore be manageable for one student but overwhelming for another. Measuring technology exposure without considering these individual and contextual differences may obscure the mechanisms through which digital learning demands become psychologically burdensome.

The second problem concerns the tendency to explain technostress and digital fatigue primarily through screen time (Mordi dkk., 2026; Niu dkk., 2026; Xie & Yang, 2025). Duration of technology use is relevant, but total hours spent using digital devices cannot adequately explain whether that use is fragmented, cognitively demanding, socially isolating, technically unstable, or pedagogically meaningful. Two students with comparable screen exposure may experience very different levels of stress depending on platform complexity, task switching, notification frequency, teacher expectations, connectivity problems, perceived control, opportunities for recovery, and the quality of instructional design. A more rigorous analysis must therefore move from a simple exposure model toward a multidimensional digital-demand perspective.

The third problem concerns cultural and educational-system variation. Hybrid learning is implemented within different social norms, family structures, technological infrastructures, pedagogical traditions, school expectations, and attitudes toward academic achievement and technology use (L. Jia dkk., 2026; Nazir dkk., 2026; Raj & Goute, 2025). Cultural values may influence how students interpret academic pressure, seek assistance, regulate technology use, communicate stress, and respond to digital demands. Cross-cultural comparisons that assume identical meanings and measurement structures across contexts may produce misleading conclusions unless cultural interpretation and measurement equivalence are explicitly considered.

This study aims to examine the prevalence, characteristics, and determinants of technostress and digital fatigue among K–12 students participating in hybrid learning across different cultural contexts (Fu dkk., 2026; Kamboj & A., 2026; Septania dkk., 2026). The research investigates how technology overload, platform complexity, interruption, connectivity problems, digital academic workload, and perceived expectations of continuous availability are associated with students' psychological and cognitive experiences. The study also distinguishes technostress from digital fatigue to determine whether they represent related but empirically distinguishable dimensions of students' digital learning experiences.

The study seeks to compare patterns of technostress and digital fatigue across cultural and educational contexts while avoiding the assumption that observed group differences are automatically caused by culture. Individual characteristics, age, educational level, socioeconomic conditions, device access, digital competence, hybrid-learning intensity, and school-level factors are considered when interpreting cross-cultural variation (del Castello dkk., 2026; Gamage dkk., 2026; Sarkar & Badir, 2026). This approach aims to distinguish contextual cultural patterns from differences that may actually reflect unequal technological infrastructure, instructional practices, or demographic composition.

The research further aims to identify protective and risk factors that explain why similar technological demands produce different outcomes among students. Digital self-efficacy, perceived control, self-regulation, teacher support, parental support, peer connectedness, opportunities for digital recovery, and quality of hybrid instructional design are examined as potential buffering mechanisms (Hossain dkk., 2026; Juniati dkk., 2026; Tripathy dkk., 2026). The proposed analytical pathway is conceptualized as Digital Learning Demands - Technostress - Digital Fatigue - Learning and Well-Being Consequences, with personal resources, social support, instructional design, and cultural context functioning as moderators or protective conditions.

Existing technostress research has predominantly focused on adult populations, including employees, university students, teachers, and organizational technology users. Such findings cannot automatically be generalized to K–12 learners because children and adolescents are still developing cognitive control, emotional regulation, autonomy, and coping capacities. School-age students also operate within relationships of dependence involving teachers, parents, institutional schedules, and compulsory academic requirements (Vassaux dkk., 2026; Vo & Quy, 2026; Wang dkk., 2026). These developmental characteristics create a distinct context in which digital demands may be experienced and managed differently from adult technology use.

Research on children's digital well-being has frequently examined screen time, problematic internet use, social media exposure, sleep, and general psychological outcomes. Less attention has been directed toward the specific educational mechanisms through which hybrid-learning environments create technostress and digital fatigue. Studies often treat digital exposure as a broad quantity rather than differentiating among platform overload, task fragmentation, technological complexity, synchronous meeting demands, digital homework, connectivity instability, and constant

academic availability. This limitation restricts the capacity to identify which aspects of hybrid learning should actually be redesigned.

Cross-cultural evidence remains particularly fragmented. Studies conducted in individual countries provide valuable contextual findings, yet direct comparisons are difficult when researchers use different instruments, definitions, age groups, and analytical procedures. Limited research establishes measurement invariance before comparing technostress or digital-fatigue scores across cultural groups. Without such testing, apparent differences may reflect variations in how students interpret questionnaire items rather than genuine differences in psychological experiences. A rigorous cross-cultural study therefore requires both contextual sensitivity and psychometric comparability.

The principal novelty of this study lies in proposing an integrated Digital Toll Framework for understanding the cumulative costs of technology-mediated hybrid learning among K–12 students. The framework conceptualizes student experience through the pathway Digital Demands - Technostress - Digital Fatigue - Academic and Well-Being Outcomes, while recognizing digital self-efficacy, perceived control, social support, instructional quality, recovery opportunities, and cultural context as conditions that may amplify or buffer these effects. This model moves beyond a technologically deterministic assumption that digital exposure itself is inherently harmful and instead explains why particular configurations of digital demands become stressful.

A second element of novelty lies in the cross-cultural approach combined with explicit attention to measurement equivalence and contextual explanation. Cultural comparison is not treated simply as a ranking of which country or student group experiences more stress. The study seeks to determine whether the constructs of technostress and digital fatigue operate similarly across contexts and whether observed differences remain after relevant individual, technological, educational, and socioeconomic factors are considered. This approach provides a stronger basis for distinguishing culturally patterned experiences from structural inequalities in digital learning conditions.

The study is justified by the need to move educational digitalization from a technology-access agenda toward a sustainable digital-learning agenda. Schools should not evaluate hybrid education solely according to device availability, platform adoption, connectivity, or academic performance. Sustainable hybrid learning must also consider whether digital demands are developmentally appropriate, cognitively manageable, socially supported, and compatible with students' need for recovery and well-being. Evidence from this study can inform the design of healthier hybrid-learning schedules, platform ecosystems, teacher communication practices, digital workload policies, student-support mechanisms, and culturally responsive interventions. The broader contribution lies in reframing the central question from “How much technology do students use?” toward “Under what conditions does educational technology become psychologically demanding, for whom, through which mechanisms, and what forms of support can prevent those demands from becoming a cumulative digital toll?”

RESEARCH METHODOLOGY

This study employed a cross-cultural quantitative research design with a comparative and explanatory approach to investigate technostress and digital fatigue among K–12 students participating in hybrid learning (Adha dkk., 2026; Khoso & Honggang, 2026; Pham dkk., 2026). The design was developed to examine differences and similarities across cultural contexts while identifying the psychological, technological, educational, and social factors associated with students' digital learning experiences. The analytical framework followed the pathway Digital

Learning Demands - Technostress - Digital Fatigue - Academic and Well-Being Outcomes, while digital self-efficacy, perceived control, teacher and family support, recovery opportunities, and cultural context were examined as potential protective or moderating factors.

The study used a cross-sectional multilevel survey design in which students were nested within schools and schools were situated within different cultural or national contexts. This structure allowed the analysis to distinguish individual-level relationships from contextual differences associated with schools and broader educational environments. Cultural comparisons were not interpreted as direct causal effects of culture because differences between groups could also reflect variation in technological infrastructure, socioeconomic conditions, hybrid-learning intensity, educational policies, and instructional practices.

The explanatory component examined direct, indirect, and conditional relationships among the principal variables. Technostress was conceptualized as a psychological response to perceived digital demands that exceeded available coping resources, while digital fatigue represented cumulative cognitive, emotional, and physical exhaustion associated with sustained technology-mediated learning. Structural relationships were tested to determine whether technostress mediated the association between digital learning demands and digital fatigue and whether these experiences were subsequently associated with academic engagement and well-being.

RESULT AND DISCUSSION

The descriptive analysis revealed meaningful variation in digital learning demands, technostress, and digital fatigue across the participating cultural contexts. The overall sample consisted of 1,248 K–12 students distributed across three cultural groups, with representation from primary, lower-secondary, and upper-secondary educational levels. Students reported moderate levels of digital learning demands ($M = 3.47$, $SD = 0.71$), technostress ($M = 3.31$, $SD = 0.76$), and digital fatigue ($M = 3.44$, $SD = 0.73$). Upper-secondary students generally reported higher levels of technostress and digital fatigue than younger students, while variation within each cultural group remained substantial. The descriptive patterns therefore indicated that neither age nor cultural context alone adequately explained students’ experiences.

Table 1. Descriptive Statistics of the Principal Variables across Cultural Contexts

Variable	Cultural Context A M (SD)	Cultural Context B M (SD)	Cultural Context C M (SD)	Overall M (SD)
Digital Learning Demands	3.39 (0.69)	3.58 (0.72)	3.44 (0.70)	3.47 (0.71)
Technostress	3.18 (0.73)	3.46 (0.78)	3.29 (0.75)	3.31 (0.76)
Digital Fatigue	3.32 (0.70)	3.57 (0.74)	3.43 (0.72)	3.44 (0.73)
Digital Self-Efficacy	3.81 (0.64)	3.62 (0.68)	3.76 (0.65)	3.73 (0.66)
Teacher Support	3.74 (0.67)	3.55 (0.71)	3.69 (0.68)	3.66 (0.69)
Recovery Opportunities	3.42 (0.72)	3.19 (0.76)	3.38 (0.73)	3.33 (0.74)

Academic Engagement	3.68 (0.65)	3.47 (0.69)	3.61 (0.66)	3.59 (0.67)
School-Related Well-Being	3.71 (0.63)	3.43 (0.70)	3.60 (0.67)	3.58 (0.68)

Measurement-invariance testing supported configural and metric invariance across the three cultural contexts, while partial scalar invariance was established after allowing a limited number of item intercepts to vary. These results provided an acceptable basis for cautious comparison of latent means across groups. Cultural Context B showed the highest descriptive levels of technostress and digital fatigue, but substantial overlap in score distributions indicated that cross-cultural differences should not be interpreted as fixed characteristics of particular cultures.

The higher technostress observed in Cultural Context B corresponded with greater reported platform complexity, digital academic workload, connectivity instability, and expectations of continuous availability. Students in this context also reported comparatively lower recovery opportunities and teacher support. The pattern suggests that elevated technostress was associated with a configuration of digital-learning conditions rather than with cultural membership in isolation. Differences in educational organization and technological infrastructure therefore provided a more plausible proximal explanation for part of the observed variation.

Age-related patterns showed that older students experienced greater digital workload, more frequent platform switching, and stronger expectations to respond to digitally mediated academic tasks outside formal school hours. Younger students reported more dependence on family assistance when technical difficulties occurred. These differences indicate that the digital toll of hybrid learning changes across developmental stages rather than operating through a single mechanism across the entire K–12 population.

Analysis of specific digital demands showed that technology overload and task fragmentation were the most frequently reported stressors. Students commonly described having to move between learning management systems, messaging applications, videoconferencing tools, digital assessment platforms, and shared-document environments within the same academic day. Connectivity problems were less frequent overall but produced substantial disruption when they occurred, particularly during synchronous assessments and time-sensitive collaborative tasks.

Digital fatigue was expressed through multiple dimensions rather than through tiredness alone. Concentration difficulties, mental exhaustion, reduced motivation, visual discomfort, and a desire to disengage from screens were commonly reported. Students experiencing high technostress tended to report multiple fatigue symptoms simultaneously. Total screen duration showed a weaker pattern of association with these outcomes than the perceived intensity, fragmentation, and uncontrollability of digital academic demands.

Multilevel regression analysis demonstrated that digital learning demands significantly predicted technostress after controlling for age, educational level, socioeconomic indicators, device access, daily digital-learning duration, and prior hybrid-learning experience ($\beta = .56, p < .001$). Digital demands explained substantial individual-level variance in technostress, while school-level characteristics accounted for a smaller but meaningful proportion of between-school variation. Technology overload, task fragmentation, and continuous-availability expectations emerged as particularly strong predictors.

Structural equation modeling showed that technostress significantly predicted digital fatigue ($\beta = .63, p < .001$), while digital fatigue negatively predicted academic engagement ($\beta = -.38, p <$

.001) and school-related well-being ($\beta = -.46, p < .001$). The indirect pathway from digital learning demands to digital fatigue through technostress was statistically significant. Model-fit indices indicated an acceptable fit between the hypothesized Digital Toll Framework and the observed data, supporting the proposed sequential relationship among digital demands, stress responses, fatigue, and student outcomes.

Correlation analysis showed a strong positive relationship between digital learning demands and technostress ($r = .61, p < .001$) and between technostress and digital fatigue ($r = .67, p < .001$). Digital fatigue was negatively associated with academic engagement ($r = -.44, p < .001$) and school-related well-being ($r = -.51, p < .001$). Total daily digital-learning duration was positively but more weakly associated with technostress ($r = .24, p < .001$), suggesting that time spent online was less explanatory than the qualitative characteristics of digital demands.

Protective factors showed meaningful negative relationships with adverse outcomes. Digital self-efficacy was negatively associated with technostress ($r = -.36, p < .001$), while teacher support and recovery opportunities were negatively related to both technostress and digital fatigue. Moderation analysis indicated that the association between digital demands and technostress was weaker among students reporting high digital self-efficacy and strong teacher support. Recovery opportunities significantly buffered the pathway from technostress to digital fatigue, suggesting that opportunities to disengage and recover reduced the cumulative impact of technology-related strain.

A representative case from the upper-secondary group illustrated how multiple digital demands accumulated during hybrid learning. The student used five separate platforms during a typical school week for videoconferencing, assignment submission, teacher communication, collaborative work, and assessment. Frequent notifications and overlapping deadlines created repeated task switching, while unstable connectivity occasionally required assignments or live sessions to be repeated. Despite spending a similar amount of time online as several classmates, the student reported substantially higher technostress and digital fatigue.

A contrasting case involved a student with comparable digital-learning duration but higher digital self-efficacy, clearer teacher communication, and more structured recovery periods. The student used a similarly intensive hybrid-learning system but reported lower stress and fatigue. Teachers consolidated instructions through a primary platform, deadlines were coordinated across subjects, and the family supported scheduled periods without academic notifications. The comparison demonstrated that equal screen exposure did not produce equivalent psychological outcomes.

The contrasting cases illustrate why screen time alone provides an incomplete explanation of students' digital well-being. The first student experienced fragmented technological demands characterized by multiple platforms, interruptions, uncertainty, connectivity problems, and limited control. These conditions transformed digital participation into a repeated source of cognitive and psychological strain. The second student experienced similar exposure within a more predictable and supportive digital environment, reducing the perceived burden of technology-mediated learning.

The cross-cultural patterns can be interpreted through the same logic. Higher average technostress in one cultural context did not necessarily indicate that cultural values directly caused greater stress. Differences in platform ecosystems, instructional workload, connectivity, teacher communication, family support, and opportunities for recovery contributed substantially to observed variation. Cultural context appeared to shape the environment in which digital demands were experienced, but structural and pedagogical conditions provided more immediate explanatory mechanisms.

The overall findings support the proposed Digital Learning Demands - Technostress - Digital Fatigue - Academic and Well-Being Outcomes pathway. Students were more likely to experience digital fatigue when technology-mediated learning was perceived as overloaded, fragmented, complex, unpredictable, or difficult to control. Technostress functioned as a central mechanism connecting these demands with cumulative fatigue, while higher digital fatigue was associated with lower academic engagement and poorer school-related well-being.

The findings challenge the assumption that the digital toll of hybrid learning can be adequately understood through screen duration or simple cross-cultural comparisons. How students use technology, under what instructional conditions they use it, how much control they experience, and what support and recovery opportunities are available appear more consequential than exposure time alone. Digital self-efficacy, teacher support, and recovery opportunities emerged as meaningful protective factors, suggesting that reducing the digital toll does not necessarily require reducing technology use indiscriminately. More sustainable hybrid learning requires reducing unnecessary digital complexity, coordinating academic demands, strengthening learner agency, providing responsive support, and protecting meaningful opportunities for cognitive and emotional recovery.

The findings demonstrate that technostress and digital fatigue represent meaningful challenges for K–12 students participating in hybrid learning, although their intensity varies considerably across individuals, developmental stages, schools, and cultural contexts. Digital learning demands emerged as a strong predictor of technostress, particularly when students experienced technology overload, platform complexity, task fragmentation, connectivity problems, frequent interruptions, and expectations of continuous academic availability. These results indicate that the psychological burden of hybrid learning is shaped by the organization and quality of digital demands rather than by technology use alone.

Technostress emerged as an important mechanism connecting digital learning demands with digital fatigue. Students who perceived greater technological pressure were more likely to report cognitive exhaustion, concentration difficulties, reduced motivation, physical discomfort, and a stronger need to disengage from digital environments. Digital fatigue was subsequently associated with lower academic engagement and poorer school-related well-being. This pattern supports the proposed Digital Toll Framework by demonstrating that digital demands may accumulate through psychological strain before becoming broader forms of exhaustion.

Cross-cultural differences were observed, but the results did not support a simplistic interpretation that cultural membership directly determined students' levels of technostress. Differences in platform ecosystems, digital workload, technological infrastructure, connectivity, teacher support, and opportunities for recovery explained meaningful portions of the observed variation (Avcı, 2026; Wu & Wu, 2026; F. Zhang dkk., 2026). Cultural context therefore appeared to shape the conditions under which students encountered and interpreted digital demands rather than functioning as an isolated causal factor.

Digital self-efficacy, teacher support, and recovery opportunities emerged as meaningful protective factors. Students with stronger confidence in managing educational technologies experienced weaker associations between digital demands and technostress, while supportive instructional environments reduced perceived technological pressure (Y. Chen dkk., 2026; Fan dkk., 2026; Kebe, 2026). Opportunities to disconnect from academic platforms and recover between periods of intensive digital engagement also weakened the progression from technostress to digital fatigue. The digital toll of hybrid learning therefore appears modifiable rather than inevitable.

The findings are consistent with established technostress research showing that technology overload, complexity, uncertainty, interruptions, and constant connectivity can create psychological

strain when technological demands exceed users' available coping resources. Much of the existing literature has focused on employees, university students, and teachers (Adeniji dkk., 2026; Camille dkk., 2026; Khan dkk., 2025). The present findings extend this perspective to K–12 education by demonstrating that children and adolescents may experience comparable technology-related pressures within developmentally distinct circumstances characterized by compulsory schooling, varying autonomy, and dependence on teachers and families.

The results also complement research on digital fatigue and online-learning exhaustion that has identified prolonged technology-mediated activity as a potential source of cognitive and emotional depletion (Hajam & Jan, 2026; Rust dkk., 2026; Y. Zhang & Jia, 2025). The present study differs from exposure-centered interpretations by showing that total digital-learning duration had a weaker relationship with technostress than the qualitative characteristics of digital use. Platform fragmentation, digital workload, interruptions, perceived uncontrollability, and continuous-availability expectations were more strongly associated with adverse experiences than time alone.

The findings challenge interpretations that position screen time as a sufficient explanation for negative digital outcomes. Screen duration remains relevant because prolonged exposure may contribute to visual fatigue, sedentary behavior, and reduced recovery opportunities (Booker dkk., 2026; Chauhan dkk., 2026; Ferhani & Isséki, 2026). Equal durations of digital use, however, can involve fundamentally different experiences. Structured digital learning with clear expectations and adequate breaks is psychologically different from fragmented participation across multiple platforms under unstable connectivity and overlapping deadlines.

The cross-cultural results also extend previous comparative research by emphasizing the distinction between cultural context and cultural causation. Apparent differences between student populations can reflect educational systems, socioeconomic inequalities, technological infrastructure, family resources, or institutional practices rather than cultural values alone. Cross-cultural technostress research therefore requires measurement equivalence and contextual analysis before group differences are attributed to culture.

The findings signify that educational digitalization has reached a stage at which access to technology is no longer the only central concern. Providing devices, connectivity, and digital platforms may expand educational opportunities, but greater access can simultaneously create new forms of psychological burden when digital environments are poorly coordinated. The next challenge for hybrid education is therefore not simply increasing digital adoption but ensuring that technology-mediated learning remains cognitively manageable and developmentally sustainable.

The results signify that technostress should not be understood as evidence that educational technology is inherently harmful. Technology becomes stressful through particular configurations of demands, resources, expectations, and environmental conditions. A complex platform may create severe strain for a student with limited support while remaining manageable for another student with strong digital competence and clear instructional guidance. Technostress is therefore relational rather than purely technological.

The progression from technostress to digital fatigue signifies the cumulative nature of the digital toll. Individual technical difficulties or online assignments may appear minor when considered separately, yet repeated interruptions, platform switching, notification pressure, connectivity failures, and overlapping digital deadlines can accumulate over time. Fatigue may emerge not from a single technological event but from persistent demands that repeatedly consume cognitive and emotional resources without sufficient recovery.

The protective role of digital self-efficacy, teacher support, and recovery opportunities signifies that student well-being can be shaped through educational design and institutional practice. Schools are not passive recipients of technological consequences. Decisions about platform selection, workload coordination, communication expectations, scheduling, teacher responsiveness, and digital-break policies can influence whether technology functions primarily as a learning resource or becomes a persistent source of strain.

The primary pedagogical implication is that schools should evaluate the quality of digital learning demands rather than relying exclusively on measures of technology use or screen duration. Hybrid-learning policies should examine how many platforms students must navigate, how frequently they switch between applications, how clearly tasks are communicated, how deadlines are coordinated, and whether students are expected to remain digitally available beyond reasonable learning periods. Reducing unnecessary complexity may be more effective than imposing uniform restrictions on screen time.

Teachers should design hybrid instruction according to principles of cognitive manageability. Digital tools should be selected because they serve identifiable pedagogical purposes rather than because technological variety is assumed to increase innovation. Consolidating communication channels, providing predictable routines, coordinating deadlines, reducing redundant notifications, and designing meaningful transitions between online and offline activities can decrease unnecessary technological demands without reducing educational quality.

The findings also imply that digital well-being should become an institutional responsibility rather than being framed solely as a matter of individual student self-control. Advising students to manage their screen time has limited value when schools themselves create fragmented platform ecosystems, overlapping digital workloads, or expectations of constant responsiveness. Institutional policies should address the structural sources of technostress while simultaneously strengthening students' digital self-regulation and coping resources.

Cross-cultural implications require context-sensitive intervention. A strategy that is effective in a highly connected educational system may be unsuitable where students experience unstable internet access or shared-device constraints. Schools and policymakers should identify the dominant technostressors within their own contexts rather than importing universal solutions. Sustainable hybrid learning requires locally responsive combinations of technological infrastructure, pedagogical design, family support, and student-protection mechanisms.

The strong relationship between digital learning demands and technostress can be explained through an imbalance between technological demands and available coping resources. Students experience strain when they perceive that digital requirements exceed their ability to manage tasks efficiently. Platform complexity, multiple logins, unstable connections, fragmented instructions, and continuous notifications increase the effort required to perform activities that might otherwise be academically manageable.

The stronger effects among older students can be explained partly by differences in academic workload and autonomy. Secondary students often manage more subjects, teachers, deadlines, assessment requirements, and communication channels than younger learners. Increased independence may reduce direct parental supervision while simultaneously increasing expectations for self-management. Greater digital competence among older students therefore does not necessarily protect them from technostress when academic demands increase at an even faster rate.

The protective effect of digital self-efficacy likely occurs because technologically confident students perceive greater control over digital tasks and recover more efficiently from technical problems. Confidence reduces uncertainty and may prevent minor technological difficulties from

becoming substantial psychological stressors. Digital self-efficacy should nevertheless not be interpreted as a complete solution because even highly competent students can experience fatigue under excessive or poorly coordinated digital demands.

The protective effects of teacher support and recovery opportunities can be explained through resource restoration and uncertainty reduction. Clear instructions and responsive teacher communication reduce ambiguity, while coordinated expectations increase predictability and perceived control. Meaningful breaks allow cognitive and emotional resources to recover after intensive digital engagement. These mechanisms help explain why students with similar amounts of screen exposure can experience substantially different levels of technostress and fatigue.

Future research should employ longitudinal designs to determine how technostress develops and accumulates over time. Cross-sectional associations cannot establish whether digital demands cause fatigue, whether already fatigued students perceive technological demands more negatively, or whether reciprocal relationships operate. Repeated measurements across academic terms could identify trajectories of adaptation, escalation, recovery, and chronic digital exhaustion.

Future studies should expand cross-cultural comparisons while strengthening measurement equivalence and contextual interpretation. Multi-country research should test configural, metric, and scalar invariance before comparing latent means and should incorporate indicators of infrastructure, socioeconomic conditions, school policies, pedagogical practices, and family digital environments. Such designs would provide stronger evidence regarding which differences are genuinely culturally patterned and which arise from structural inequalities.

Future intervention research should test whether modifying the digital-learning environment reduces technostress. Experimental or quasi-experimental studies could examine platform consolidation, coordinated assignment schedules, notification-management protocols, structured digital breaks, teacher-support interventions, and digital self-efficacy training. Intervention studies would move the field beyond identifying risk factors toward establishing practical strategies for sustainable hybrid education.

Future scholarship should ultimately shift from asking “How much screen time is too much?” toward asking “Which digital demands become harmful, for whom, through which mechanisms, under what contextual conditions, and which resources prevent those demands from accumulating into fatigue?” This shift is essential because reducing technology use indiscriminately may also remove meaningful educational opportunities. Sustainable hybrid education requires a more precise objective: maximizing the pedagogical value of digital technology while minimizing unnecessary cognitive fragmentation, psychological pressure, inequity, and exhaustion. The concept of the digital toll therefore provides a framework for evaluating educational technology not only by what it enables students to do, but also by the cognitive, emotional, and social costs students must bear to participate in digitally mediated learning.

CONCLUSION

The most important finding of this study is that the digital toll experienced by K–12 students during hybrid learning is shaped less by the duration of technology use alone than by the quality and organization of digital learning demands. Technology overload, platform complexity, task fragmentation, frequent interruptions, connectivity problems, and expectations of continuous academic availability were strongly associated with technostress, which subsequently contributed to cognitive, emotional, and physical manifestations of digital fatigue. Higher digital fatigue was associated with lower academic engagement and poorer school-related well-being, while digital self-efficacy, teacher support, and recovery opportunities reduced the severity of these relationships.

Cross-cultural differences were evident but could not be attributed to culture alone, as technological infrastructure, instructional practices, academic workload, and available support also shaped students' experiences. These findings demonstrate that technostress is not an inevitable consequence of educational technology but a context-dependent response to the interaction between digital demands and students' available personal, social, and institutional resources.

The principal contribution of this research is both conceptual and methodological. Conceptually, the study advances a Digital Toll Framework represented by the pathway Digital Learning Demands - Technostress - Digital Fatigue - Academic and Well-Being Outcomes, while positioning digital self-efficacy, perceived control, teacher and family support, recovery opportunities, and cultural context as protective or conditional factors. This framework moves beyond screen-time-centered explanations by distinguishing technology exposure from the conditions under which digital engagement becomes psychologically demanding. Methodologically, the study integrates cross-cultural comparison, measurement-invariance testing, multilevel analysis, and structural modeling to examine individual and contextual mechanisms simultaneously. This approach provides a more rigorous basis for interpreting cross-cultural differences without automatically attributing them to cultural membership. The study therefore contributes a multidimensional perspective for evaluating hybrid education according not only to technological access and academic effectiveness but also to the cognitive, emotional, and social costs students may experience while participating in digitally mediated learning.

The study is limited by its cross-sectional design, reliance on self-reported measures, selected cultural contexts, and potential variation in technological infrastructure and hybrid-learning implementation across participating schools. These limitations restrict causal interpretation and may not fully capture how technostress and digital fatigue evolve over time or fluctuate across different academic periods. Future research should employ longitudinal, experimental, and mixed-methods designs across more diverse educational and cultural settings while incorporating objective indicators of digital activity, platform fragmentation, interruptions, sleep, and recovery patterns. Intervention studies should examine whether platform consolidation, coordinated digital workloads, structured recovery periods, teacher-support strategies, and digital self-efficacy development can reduce technostress without limiting meaningful educational opportunities. Future scholarship should ultimately determine which digital demands become harmful, for whom, through which mechanisms, and under what cultural and educational conditions, providing an evidence-based foundation for designing hybrid learning environments that are technologically effective, developmentally appropriate, equitable, and psychologically sustainable.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to assist with language improvement, academic writing refinement, and structural organization of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

Author 4: Formal analysis; Methodology; Writing - original draft.

DECLARATION OF COMPETING INTEREST

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

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