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Computational Complexity, Quantum Advantage, and Inclusive Design: A Conceptual Analysis of Educational and Assistive Technologies

Catello Cascone [1], Marco Caruso [2]*, Michele Domenico Todino [1], Vincenzo Loia [1]

[1] Università degli studi di Salerno; cacascone@unisa.it; mtodino@unisa.it; loia@unisa.it
[2] Università degli studi di Macerata; m.caruso9@unimc.it
* Correspondence: m.caruso9@unimc.it

Abstract: Recent advances in quantum computing have renewed interest in potential computational advantages for problems that are difficult or impractical under classical approaches. Yet, their implications for educational and assistive technologies, especially from an inclusive, human-centered perspective, remain insufficiently explored. This paper addresses this gap by examining "quantum advantage" through the lens of computational complexity and inclusive design. The work adopts a conceptual and interpretative methodology, drawing on interdisciplinary literature in computer science education, human-computer interaction, and inclusive pedagogy. Rather than reporting empirical experiments, it synthesizes recurring patterns and design constraints that emerge when advanced computational paradigms are translated into educational and assistive contexts. The analysis indicates that increasing computational sophistication is systematically associated with higher levels of abstraction and cognitive load, which may hinder accessibility if left unmediated. It also shows that interaction design, visualization, and multimodal interfaces function as essential mediators, enabling interpretability and supporting heterogeneous users. At the same time, limitations related to technological maturity, transparency, and ethical accountability delimit the conditions under which claims of quantum advantage remain credible. Overall, quantum advantage in educational and assistive technologies should be understood as a conditional and mediated phenomenon, emerging from the interplay between computational acceleration, pedagogical scaffolding, interactional design, and human agency, rather than as an intrinsic property of computation alone.

Keywords: Computational complexity; quantum advantage; inclusive design; assistive technologies; human-computer interaction

1. Introduction

To understand the role and the limitations of algorithms in the contemporary world, it is necessary to introduce the concept of computational complexity, that is, the study of the resources, particularly computational time, required by an automated procedure to solve a problem as the size of the input data increases. In theoretical

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computer science, this analysis does not concern the performance of a specific physical machine, but rather the abstract properties of algorithms themselves, independently of the hardware on which they are implemented. For this purpose, problems are grouped into complexity classes, among which P, NP, and NP-complete (which will be briefly described below) constitute a fundamental reference framework for assessing whether a solution is not only logically correct, but also practically feasible.

The distinction among these classes has implications that extend well beyond the technical domain. Indeed, it influences the design of information systems, cryptographic security, the optimization of economic and industrial processes, and, more broadly, the possibility of translating theoretical models into reliable operational tools. In the contemporary educational context, additional forms of complexity frequently arise from human-machine interactions that exceed the models associated with traditional interfaces. This scenario directly involves the study and design of systems capable of substituting for or enhancing sensory channels, as well as increasing the levels of safety, redundancy, and reliability required when interacting with users who present special educational needs. Within this framework, system design does not merely fulfill a technical function, but becomes a central element in ensuring accessibility, inclusion, and continuity of the educational experience.

In general, an algorithm that, in the worst case, requires unpredictable or excessively long computation times cannot be integrated into real-world applications, as it violates essential requirements such as reliability, reproducibility, and economic sustainability. From this perspective, complexity theory establishes a clear boundary between what is conceptually solvable and what is effectively usable. Accordingly, the distinction among different types of algorithms can be interpreted as a classification of the practical limits of automatic computation.

Algorithms belonging to class P represent "stable" computational procedures: as problem complexity grows, their execution time increases in a controlled and predictable manner, making them suitable for integration into everyday technologies and reliable institutional systems. Problems in class NP, by contrast, introduce a conceptual fracture between knowing a solution and finding one: while verifying a candidate solution can be done efficiently, identifying it may require a combinatorial exploration that, in the worst case, grows beyond any threshold of practical sustainability. This difficulty reaches its maximum in NP-complete problems, for which computation time may increase exponentially, yielding algorithms that, although formally correct, are unusable in real application contexts because they do not guarantee termination within acceptable finite timeframes (Sedgewick, 2000; Ghezzi, Jazayeri, Mandrioli, 2004; Mandrioli, Spoletini, 2011).

In concrete terms, a machine that risks becoming "trapped" in an endless search cannot be designed, certified, or commercialized. The potential advent of quantum computing fits into this framework as a moment of historical discontinuity: by exploiting non-classical physical properties, it promises to reorganize the way solution spaces are explored, drastically reducing the time required for certain computations that are currently prohibitive (Parisi, 2025). Even without eliminating the theoretical distinction between P and NP, quantum computers could make practically usable algorithms that today remain confined to the theoretical domain, thereby altering the relationship between mathematical abstraction, technology, and social application (ibid.).

What makes fields of knowledge characterized by rapid expansion particularly compelling is their ability to catalyze the interest and engagement of new generations of researchers. This attractive force also lies in the opportunity, offered by advanced theoretical frameworks such as quantum physics, to formulate inferences and predictions about what is "knowable" based on what is already "known" (Silvestrini, 2025). This perspective is fully relevant when scientific and technological progress is oriented toward serving human beings, particularly in care-related activities mediated by machines and intelligent systems. In such contexts, the advancement of knowledge necessarily proceeds along interdisciplinary trajectories, in which dialogue among the hard sciences, the human sciences, and applied practices becomes an essential condition for responsible and meaningful development.

At this stage, an initial interdisciplinary reflection is required: in the domain of educational and assistive technologies, the selection of algorithms cannot disregard, but must explicitly account for, constraints related to response time, computational stability, and the reliability of human-machine interaction, all characteristics that recall the properties and principles of semplessità (Berthoz, 2011; Sibilio, 2014, 2023). From this standpoint, complexity theory provides an essential conceptual framework for understanding why certain algorithms, although well-defined and mathematically correct, are in fact unusable in real-world applications designed for people with disabilities.

Algorithms in class P, such as Dijkstra's algorithm for the shortest path, Kruskal's algorithm for the minimum spanning tree, sorting algorithms like Merge Sort and Quick Sort, or Binary Search (Sedgewick, 2000), constitute the operational backbone of many assistive technologies. They guarantee polynomial and predictable execution times, a prerequisite for applications such as text-to-speech systems, lexical prediction in facilitated writing software, eye-tracking systems, and assisted navigation for users with motor or cognitive disabilities.

By contrast, many problems that are central to educational personalization fall within class NP. Classic examples include the Knapsack Problem, the Boolean Satisfiability Problem (SAT), and the verification of puzzle solutions such as Sudoku. In educational contexts, these problems emerge when verifying the coherence of a personalized learning plan, checking the correctness of an Augmentative and Alternative Communication (AAC) configuration (Galdieri & Sibilio, 2021; Galdieri & Zappalà, 2021; Galdieri, 2022), or automatically validating the grammatical and semantic structure of a text produced by a student with specific learning disorders. In such cases, although solution verification is computationally efficient, the search for an optimal solution remains complex.

The situation becomes particularly critical for NP-complete problems, including the Travelling Salesperson Problem (TSP), 3-SAT, the Graph Coloring Problem, and the Maximum Clique Problem. These problems naturally model many advanced requirements of assistive technologies: the global optimization of multisensory interfaces for individuals on the autism spectrum, the path planning of assistive robots (Campitiello et al., 2021; 2022a; 2022b; 2022c; Schiavo et al., 2024) in complex environments, the optimal scheduling of educational or rehabilitative interventions, and the dynamic adaptation of instructional content in adaptive learning systems. However, exact algorithms for these problems exhibit exponential worst-case complexity, making their direct use impossible in systems that must provide real-time responses.

For this reason, educational and assistive applications extensively rely on approximation algorithms, heuristic algorithms, and metaheuristics such as greedy algorithms, local search, simulated annealing, genetic algorithms, and ant colony optimization. These approaches do not guarantee optimal solutions, but they produce sufficiently good results within timeframes compatible with human interaction, thereby preserving the continuity of the educational experience and the reliability of the system.

Although NP-complete algorithms cannot be directly employed in their exact form, they nonetheless play a fundamental theoretical role: they define the upper bound of achievable optimization and guide the design of hybrid systems in which complexity is reduced through pedagogical constraints, contextual simplifications, and user models derived from research in special education. From this perspective, the contribution of educational sciences is not ancillary but structural, as it enables a restriction of the computationally relevant solution space.

The potential maturation of quantum computing and of quantum algorithms such as Grover's search algorithm and Shor's algorithm could significantly modify the current balance between tractable and intractable problems. While such developments do not eliminate the theoretical distinction between P and NP, they may render operationally viable certain algorithms that are currently confined to theoretical research, opening new possibilities for the design of highly personalized assistive technologies. Even in this scenario, however, pedagogical reflection on the relationship between computational optimization, system transparency, and human control in educational and inclusive processes would remain central.

The theoretical framework of the re-ontologization of reality, as proposed by Floridi (2022), offers a particularly relevant interpretive lens. In this regard, special attention is drawn to sections 1.2, The Disaggregating Power of the Digital: "Cut and Paste" Modernity, and 1.3, New Forms of Agency, in which these dynamics are examined systematically. This framework can be further enriched by integrating the emerging role of quantum computers and the new possibilities they open with respect to the traditional limits of classical computation, particularly those associated with problems in class P.

In this scenario, quantum computing does not merely represent an increase in computational power but contributes to a more profound transformation of the very way in which we conceive computation, technological agency, and, consequently, the digital reality we inhabit. Quantum computers, grounded in principles such as superposition, entanglement, and quantum interference, introduce a mode of information processing that is radically different from that of classical computers (Benenti, Casati, Montangero, 2025; Parisi, 2025; Silvestrini, 2025). From an ontological perspective, returning to Floridi (2022), they do not simply execute the same algorithms more quickly, but enable the simultaneous exploration of large solution spaces, redefining the relationship between what is computable, what is knowable, and what is practically realizable.

This transformation directly affects the traditional distinction between tractable problems (class P) and intractable problems, such as those belonging to NP and NP-complete classes. Although quantum computing does not automatically imply polynomial-time solutions for all NP-complete problems, it introduces new complexity classes (such as Bounded-Error Quantum Polynomial Time) that expand the space of efficiently executable algorithms. Well known quantum algorithms, including

Grover's algorithm for unstructured search and Shor's algorithm for integer factorization, demonstrate how problems considered computationally demanding or practically inaccessible in the classical paradigm may become tractable in a quantum context.

In this sense, quantum computing does not merely transcend the boundaries of class P, but contributes to redefining them, calling into question the established hierarchy of computational difficulty. This redefinition has implications that extend beyond the technical sphere and fully participates in the process of re-ontologization described by Floridi (2022). The possibility of implementing algorithms that operate in quantum probability spaces and exploit non-classical physical properties generates new forms of artificial agency, in which computational action is no longer reducible to a deterministic sequence of steps, but assumes an intrinsically probabilistic and relational nature. Consequently, the epistemological categories through which we interpret the functioning of machines and their role in human contexts prove inadequate if they remain anchored exclusively to classical computation.

In the fields of education, care, and assistive technologies, these developments generate unprecedented perspectives. The ability to address complex optimization problems more effectively, such as the fine-grained personalization of educational pathways, the dynamic adaptation of multisensory interfaces, or the planning of highly individualized interventions, suggests that algorithms currently confined to the theoretical sphere may become operationally relevant. In this sense, quantum computing contributes not only to a re-engineering of technical solutions, but to a genuine re-ontologization of educational and assistive action, insofar as it modifies the conditions of possibility of action itself.

Therefore, the integration of quantum computing, artificial intelligence, and philosophical reflection on the re-ontologization of reality allows us to understand how contemporary digital technologies are giving rise to an epochal transformation: not merely a new technology, but a new ontological and epistemological environment in which the boundaries of the computable, the knowable, and human agency mediated by artificial tools are being redefined.

2. Materials and Methods

The present work adopts a conceptual and interpretative methodological approach rather than an experimental or data-driven one. The objective of the paper is not to introduce or validate a new computational system, but to provide a theoretically grounded analysis of the relationship between computational complexity, emerging quantum computing paradigms, and the design of educational and assistive technologies from an inclusive perspective.

The methodological framework is inspired by recent interdisciplinary research at the intersection of computer science education, human-computer interaction, and inclusive pedagogy. In particular, the analysis draws upon consolidated findings from the literature on quantum computing education, which highlights recurrent challenges related to abstraction, cognitive load, learner heterogeneity, and accessibility. These challenges are examined here as representative instances of broader issues that arise when highly complex computational paradigms are translated into human-centered systems.

Rather than conducting a systematic review or a meta-analysis, this work follows an interpretative synthesis approach. Selected contributions from the literature are analyzed qualitatively to identify recurring conceptual patterns, design principles, and limitations that are relevant to inclusive educational and assistive contexts. A clear distinction is maintained between empirically validated educational practices and forward-looking or conceptual proposals, allowing the discussion to remain grounded in current capabilities while also addressing plausible future developments.

The analysis is structured around a set of thematic dimensions that guide the interpretation of the selected works. These dimensions include: (i) the role of computational complexity and algorithmic tractability in interactive systems; (ii) the cognitive and pedagogical implications of non-classical computational models; (iii) the function of visualization, interaction, and multimodal interfaces in mediating abstract computational processes; and (iv) the implications of these factors for accessibility, inclusion, and reliability in educational and assistive technologies. These themes provide a coherent framework for linking theoretical insights from complexity theory and quantum computing to concrete design considerations.

No original datasets, experimental protocols, or human or animal studies are reported in this work. Consequently, no ethical approval was required. All references discussed are publicly available and are cited appropriately. Where applicable, examples of technologies and applications are used illustratively to support the conceptual argument, without claiming empirical validation beyond what is reported in the original sources.

3. Results

This section reports the main analytical outcomes of the interpretative framework adopted in this work. Rather than presenting quantitative experimental results, the findings reported here consist of recurring conceptual patterns and design implications that emerge from the qualitative analysis of the selected literature. These results provide a structured synthesis of how computational complexity and advanced computational paradigms interact with educational and assistive design requirements.

3.1 Emerging Patterns from the Literature

A consistent pattern emerging from the analyzed literature concerns the tight coupling between algorithmic sophistication and increasing levels of conceptual abstraction. Studies addressing advanced computational paradigms in educational contexts repeatedly report that as algorithms move beyond deterministic and polynomial-time models, learners encounter substantial interpretative difficulties, particularly when underlying computational processes are opaque or non-intuitive (Cuenca-Grau, 2004; Donhauser et al., 2024).

This pattern is especially evident in the domain of quantum computing education, where the transition from classical to non-classical computation introduces probabilistic reasoning, superposition-based state representations, and non-deterministic outcomes. Empirical analyses of quantum education platforms and curricula show that learners without a strong background in mathematics or theoretical physics experience a sharp increase in cognitive load when exposed directly to these abstractions without sufficient scaffolding or mediation (Donhauser et al., 2024; Satanassi et al., 2022).

At the same time, the literature highlights that many educational systems implicitly mitigate these barriers through modular curricular structures, progressive disclosure of complexity, and guided interaction paradigms. Large-scale online initiatives, such as MOOC-based quantum education programs, demonstrate that when advanced computational content is organized along flexible learning paths, learners from heterogeneous disciplinary and educational backgrounds can engage meaningfully with otherwise inaccessible topics (Hellstern et al., 2024; Goorney et al., 2024).

From an inclusive education perspective, this recurring pattern suggests that accessibility is not achieved by simplifying computational models per se, but by controlling how and when complexity is exposed to the learner. Algorithmic sophistication, if left unmediated, functions as an exclusionary factor; when appropriately structured, however, it can be integrated into inclusive educational environments without compromising conceptual rigor.

3.2 Cognitive and Pedagogical Implications of Computational Complexity

A second major result concerns the cognitive mismatch between learners' intuitive reasoning strategies and the operational logic of advanced computational paradigms. Across multiple studies, learners engaging with quantum or non-classical computational models tend to rely on classical deterministic heuristics, even when such heuristics are formally invalid in probabilistic or superpositional contexts (Ashktorab et al., 2019; Donhauser et al., 2024).

This phenomenon has been explicitly documented in quantum computing education research, where students often interpret quantum circuits and algorithms through classical cause-effect frameworks, leading to persistent misconceptions unless instructional interventions are carefully designed (Satanassi et al., 2022; Zaman et al., 2023). Research-based teaching strategies, including guided inquiry, structured problem decomposition, and conceptual scaffolding, have been shown to significantly reduce these misunderstandings by aligning instructional design with learners' evolving mental models (Donhauser et al., 2024).

From a pedagogical standpoint, these findings highlight that computational complexity is not merely a technical attribute of algorithms, but a cognitive challenge that directly affects usability and learning outcomes. In educational and assistive technologies, this challenge becomes particularly critical, as users may already experience cognitive, sensory, or attentional constraints. Systems that expose users to non-classical computational behavior without adequate mediation risk amplifying exclusion rather than enabling participation.

The literature further suggests that pedagogical mediation must operate at multiple levels: conceptual (through explanatory metaphors and analogies), interactional (through feedback and visualization), and temporal (through pacing and progressive complexity). These strategies collectively function as cognitive stabilizers, enabling users to engage with advanced computation without being overwhelmed by its formal complexity (Ashktorab et al., 2019).

3.3 Interaction, Visualization, and Accessibility as Mediating Factors

A third set of results emphasizes the central role of interaction design and visualization in mediating computational complexity. Across the reviewed studies, visualization consistently emerges as a primary gateway for making abstract computational processes accessible to human users (Fritzsche, 2014; Reinikainen et al., 2024).

Interactive quantum simulators, visual circuit builders, and multimodal learning environments allow learners to externalize internal computational states and observe the effects of algorithmic operations in real time. Empirical evidence indicates that such environments significantly reduce cognitive load and improve conceptual understanding, particularly for novice learners and non-specialist audiences (Reinikainen et al., 2024; Zaman et al., 2023).

Beyond graphical interfaces, the literature also highlights the importance of human-computer interaction principles tailored to non-deterministic systems. Research on human-quantum computer interaction identifies "thinking too classically" as a fundamental usability challenge, underscoring the need for interfaces that support exploration, uncertainty management, and interpretability rather than deterministic predictability (Ashktorab et al., 2019).

From an accessibility perspective, these findings suggest that interaction and visualization are not auxiliary components, but structural enablers of inclusion. Multimodal interfaces, tangible representations, and immersive environments provide alternative access channels for users with diverse cognitive and sensory profiles. Although most existing systems do not explicitly evaluate inclusivity outcomes, their design choices implicitly align with inclusive principles by lowering entry barriers and supporting heterogeneous modes of engagement (Zable et al., 2020; Violaris, 2023).

3.4 Empirical Evidence on Scalability and Inclusivity in Advanced Educational Systems

Empirical evidence from large-scale deployments further reinforces the relationship between scalability and inclusivity in advanced educational technologies. MOOC-based quantum education initiatives demonstrate that scalable platforms can reach diverse learner populations, provided that instructional design incorporates flexibility, guided pathways, and adaptive feedback mechanisms (Hellstern et al., 2024; Goorney et al., 2024).

Analyses of learner participation and success rates reveal that engagement, rather than prior expertise, is a primary predictor of learning outcomes. This finding suggests that inclusive access to advanced computational education is achievable when systems are designed to accommodate heterogeneous entry points and learning trajectories (Hellstern et al., 2024).

However, the literature also reveals persistent limitations, including high dropout rates and uneven participation, indicating that scalability alone does not guarantee inclusivity. These results highlight the need for further research on adaptive support mechanisms and accessibility-aware evaluation frameworks (Goorney et al., 2024).

3.5 Synthesis of Design Constraints and Boundary Conditions

Finally, the analysis identifies a set of boundary conditions that constrain the practical integration of advanced computational paradigms into educational and assistive technologies. These include the current technological maturity of quantum systems, the limited availability of inclusivity-specific evaluation metrics, and the risk of overextending claims of computational or quantum advantage beyond empirically supported contexts (Hou et al., 2021; Rönkkö et al., 2024).

Recognizing these constraints constitutes a critical result of the present analysis, as it delineates the conditions under which advanced computation can be responsibly and effectively translated into human-centered systems.

4. Discussion

4.1 Interpreting Quantum Advantage Through the Results of This Study

The notion of quantum advantage discussed in this work can be interpreted meaningfully only in light of the analytical results presented in Section 3. Taken together, these results show that the potential benefits of advanced computational paradigms are not independent from cognitive, pedagogical, and interactional constraints that shape human-machine engagement in educational and assistive contexts.

First, Section 3.1 indicates that increasing computational sophistication is systematically associated with higher levels of abstraction and cognitive load. This finding challenges any assumption that quantum computing, by virtue of computational power alone, would naturally enhance accessibility or inclusion. On the contrary, the transition toward non-classical models risks amplifying barriers unless complexity is carefully mediated through design choices that regulate how and when advanced functionality is exposed to users.

Second, the implications discussed in Section 3.2 further qualify the conditions under which quantum advantage may become relevant. The mismatch between learners' intuitive reasoning strategies and the probabilistic logic of non-classical computation suggests that computational acceleration does not automatically translate into improved usability or learning outcomes. Without adequate pedagogical scaffolding, advanced computational systems may remain opaque, reinforcing exclusion rather than supporting participation.

Third, Section 3.3 reinforces this interpretation by showing that interaction design and visualization function as structural mediators of computational complexity. Visualization, multimodality, and interaction are enabling conditions that determine whether advanced computation can be appropriated by human users. Consequently, claims of quantum advantage in educational and assistive technologies presuppose interfaces capable of rendering non-deterministic processes interpretable and cognitively manageable.

Moreover, the empirical evidence discussed in Section 3.4 adds a further constraint: scalability alone does not guarantee inclusivity. Uneven participation patterns indicate that the benefits of computational sophistication may accrue selectively, depending on users' prior knowledge, cognitive resources, and access to supportive learning structures. Finally, the boundary conditions identified in Section 3.5, technological immaturity, limited inclusivity-aware evaluation metrics, and the risk of overstating near-term applicability, delineate the space within which quantum advantage claims remain credible.

In this sense, quantum advantage in educational and assistive technologies should be framed as a conditional and mediated phenomenon. It does not reside in quantum computation itself, but in the interplay between computational acceleration, pedagogical design, interactional mediation, and ethical responsibility.

4.2 Exploring Potential Applications of Quantum-Enhanced Assistive Technologies

In this section, we draw inspiration from the expression "quantum advantage" used by Benenti et al., who have described, albeit in a popular-science manner, how quantum algorithms and the quantum approach more broadly may represent a significant applied leap in addressing a wide range of problems. More specifically, we aim to identify certain assistive technologies that currently exhibit limitations, whether computational, conceptual, or structural, and that could potentially benefit from quantum computing considered in all its dimensions. Clearly, our intention is neither to imagine non-existent technologies nor to engage in speculative leaps that verge on science fiction; rather, both in the present and in the near future, we seek to connect quantum algorithms and applications that already exist with technologies that could realistically derive advantages from them.

It is important to clarify that the term "anticipation" should not be understood in a predictive or deterministic sense. In the context of quantum computing, it refers instead to the possibility of exploring complex decision spaces more efficiently, reducing the time required to identify optimal or near-optimal solutions. In this sense, quantum advantage manifests itself in the ability to accelerate specific phases of the decision-making process, such as the evaluation of alternative scenarios or the solution of optimization problems, rather than in the direct prediction of future events. More rigorously, the contribution of quantum computing to decision-making processes concerns the computational acceleration of problems that can be formalized as combinatorial optimization or search in high-dimensional spaces. Specific quantum algorithms can reduce the time complexity of these operations compared to classical approaches, thereby making decision-making processes more responsive while remaining grounded in known data and models.

A further preliminary clarification is required: quantum superposition does not imply direct and simultaneous access to all possible solutions to a problem. Rather, it allows the representation of a space of states that can be exploited through appropriately designed quantum algorithms. It is indeed the interaction among superposition, interference, and measurement that enables the amplification of relevant solutions and the suppression of less significant ones. Although a quantum system can encode an exponentially growing number of configurations as the number of qubits increases, the extraction of useful information always occurs through a measurement that yields a single outcome. Quantum advantage therefore lies in the design of algorithms capable of exploiting the evolution of the quantum state in order to increase the probability of obtaining optimal solutions.

In all the cases considered here, the contribution of quantum computing should not be understood as a direct replacement for human decision-making processes or classical systems. Rather, it should be conceived as an advanced computational support, potentially integrable within hybrid architectures, in which quantum computation acts as an accelerator for specific functions.

Against this backdrop, we attempt to envision how quantum computing might serve assistive technologies in the near future.

- The superposition state of qubits can be exploited to enhance, and to some extent "anticipate", decision-making processes. The specific nature of the qubit allows multiple configurations of the same problem to be represented simultaneously, causing the solution space to grow exponentially as the number of qubits increases. In this way, one may hypothesize applications in the field of assistive technologies, such as robotic prostheses. These devices could integrate quantum-computing modules dedicated to the interpretation of neural signals originating from the central nervous system, thereby improving the speed and precision of motor activation. Such an approach could reduce computational delays and expand the range of movements compared to currently available robotic prostheses.
- Expanding upon the previous hypothesis, it is possible to imagine that such prostheses would not be limited to compensatory devices for persons with disabilities, but could also include supplementary prostheses that extend human action in operations characterized by high levels of complexity. Consider, for example, the potential benefits for surgery deriving from instruments capable of performing extremely precise movements and incisions, controlled by surgeons through dedicated interfaces and supported by advanced computational systems based on quantum computing.
- It is also conceivable to design mobility supports capable of facilitating navigation in complex environments, such as urban neighborhoods or crowded spaces. Technologies including GPS, proximity sensors, and vision systems could cooperate with quantum-computing modules to optimize the routes of powered wheelchairs, enabling the real-time selection of paths that are faster, safer, and better suited to specific mobility needs.
- The anticipatory dimension of quantum computing could also find application in the gaming context, offering individuals with disabilities or motor impairments, for example through voice commands or alternative interfaces, the possibility to analyze the game environment and anticipate available actions. This would contribute to making interactive experiences more accessible, both offline and online, which increasingly represent important forms of entertainment and social interaction. The same could be said about edugames and Metaverse-like softwares. Inclusive contexts could be programmed and shaped keeping in mind every special need of each person with disability. Optimizing this specific human-machine interaction could revolutionize teaching and inclusion methodologies in new and innovative ways.
- One may also envision a quantum-based support system for individuals with visual impairments that, in processing video content, can produce real-time, detailed

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descriptions of what appears on the screen, without requiring prior manual annotation. Similarly, such information could be conveyed through audio description or by dynamic braille devices capable of instantly translating visual content. In this way, individuals with visual impairments could access audiovisual materials such as live broadcasts, even when no accessible description has been planned during the production phase.

- A further area of application concerns assisted communication systems, in which quantum computing could contribute to the optimization of particularly complex linguistic and semantic models. These systems often operate under conditions characterized by incomplete, ambiguous, or noisy signals, as in the case of gestural, visual, or multimodal inputs, requiring computationally demanding processes of interpretation and disambiguation. In this context, quantum algorithms dedicated to optimization and pattern matching could support a more efficient management of the space of possible interpretations, improving both the speed and accuracy of system responses. More specifically, significant support could be envisioned for sign language, where the automatic translation of gestures into spoken language requires the integration of spatial, temporal, and contextual information. The combinatorial complexity arising from the variability of movements, hand configurations, and facial expressions could benefit from advanced computational approaches capable of optimizing the correspondence between gestural sequences and linguistic structures. In this way, assistive communication systems based on visual sensors and advanced computational models could offer more fluent and contextually appropriate translations, reduce interpretative ambiguities and expand access to communication for deaf individuals or people with language impairments.

4.3 Risks, Misinterpretations, and Ethical Drift

While the potential application domains outlined above illustrate how quantum-enhanced computation could in principle support educational and assistive technologies, they also bring into focus a set of risks that must be addressed explicitly to avoid conceptual, pedagogical, and ethical drift.

A primary risk concerns the tendency to conflate computational acceleration with cognitive or educational benefit. As illustrated in the scenarios discussed in Section 4.2, faster optimization or more efficient search does not automatically translate into improved understanding, usability, or inclusion. In contexts characterized by user heterogeneity and specific educational needs, unmediated increases in computational sophistication may amplify exclusion rather than reducing it.

A further source of misinterpretation lies in the rhetorical use of the term “quantum advantage” itself.   precise computational and contextual conditions, the notion may foster unrealistic expectations regarding system capabilities, particularly when applied to sensitive domains such as assistive communication, mobility support, or sensory mediation. Such narratives risk obscuring the substantial design, pedagogical, and interactional work required to translate computational advances into meaningful human-centered applications.

System opacity represents another critical concern. Quantum algorithms operate through probabilistic processes that are intrinsically less transparent than classi-

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cal deterministic procedures. When embedded within assistive or educational systems, such as those envisioned in Section 4.2, this opacity may undermine trust, accountability, and user agency unless explicit mechanisms for explanation, monitoring, and human oversight are incorporated.

Ethical drifts may also emerge when performance-oriented metrics dominate system evaluation at the expense of accessibility, inclusivity, and user well-being. Optimization-driven approaches, even when technically successful, risk marginalizing users whose cognitive profiles or interaction styles deviate from assumed norms. In this sense, quantum-enhanced paradigms may inadvertently reinforce existing inequalities if inclusivity is treated as a secondary concern.

Finally, the risk of temporal misalignment persists between technological development and pedagogical readiness. While quantum computing research advances rapidly, educational and assistive ecosystems evolve more slowly, constrained by institutional, cultural, and ethical factors. Premature alignment between speculative technological capabilities and real-world assistive needs may compromise reliability, safety, and trust, particularly for vulnerable populations.

Taken together, these considerations reinforce the view that quantum advantage should not be framed as an inherently positive or self-justifying property of technology. Rather, it must be critically situated within an ethical and pedagogical framework that prioritizes human agency, transparency, and responsibility. Without such grounding, advances in computation risk producing systems that are technically sophisticated yet educationally fragile and ethically misaligned.

5. Conclusions

This work has examined the notion of quantum advantage through an interdisciplinary lens that combines computational complexity theory, educational sciences, human-computer interaction, and philosophical reflection on technological agency. Rather than treating quantum computing as a purely technical breakthrough, the analysis has framed it as a potential modifier of the conditions under which educational and assistive technologies are designed, evaluated, and experienced by human users.

By grounding the discussion in the established distinction between tractable and intractable computational problems, the paper has shown that algorithmic feasibility is not a neutral or abstract property, but a decisive factor in determining whether a technological solution can be responsibly integrated into real-world educational and assistive contexts. In such settings, constraints related to response time, reliability, interpretability, and cognitive accessibility are not secondary considerations, but structural requirements.

The results of the interpretative synthesis highlight that increasing computational sophistication is systematically associated with higher levels of abstraction and cognitive load. This relationship places intrinsic limits on the direct applicability of advanced computational paradigms, including quantum-based approaches, unless they are mediated through appropriate pedagogical, interactional, and design strategies. From this perspective, quantum advantage cannot be understood as an intrinsic property of computation alone, but as a conditional phenomenon emerging from the interaction between computational acceleration and human-centered system design.

The discussion has further shown that interaction design, visualization, and multimodal interfaces play a central role in translating abstract and non-deterministic computational processes into forms that are cognitively manageable and accessible. These mediating elements are particularly critical in educational and assistive technologies, where users may present heterogeneous cognitive, sensory, or motor profiles. Without such mediation, advances in computation risk reinforcing exclusion rather than promoting inclusion.

Within this framework, the exploration of potential quantum-enhanced assistive technologies has been intentionally framed in a cautious and non-speculative manner. The scenarios discussed are not intended as short-term implementation claims, but as conceptual illustrations of how quantum computing might function as an accelerator for specific sub-problems, such as optimization, search, or ambiguity management, within hybrid architectures that remain fundamentally human-controlled and pedagogically informed.

At the same time, the analysis has identified significant risks associated with uncritical or rhetorically inflated interpretations of quantum advantage. These include technological determinism, system opacity, ethical drift, and temporal misalignment between technological development and pedagogical readiness. Addressing these risks requires evaluation frameworks that explicitly incorporate accessibility, inclusivity, transparency, and user agency as primary criteria, rather than treating them as secondary outcomes of performance optimization.

In conclusion, quantum computing should not be conceived as a disruptive replacement of existing educational and assistive technologies, but as a potential contributor to their evolution, one whose value depends on careful integration within interdisciplinary, ethically grounded, and human-centered design processes. Only under these conditions can advances in computation meaningfully expand, rather than constrain, the space of the computable, the knowable, and the actionable in inclusive educational and assistive environments.

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