Multimodal Technologies and Interaction

Review

A Narrative Review of the Sociotechnical Landscape and Potential of Computer-Assisted Dynamic Assessment for Children with Communication Support Needs

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Abstract: This paper presents a narrative review of the current practices in assessing learners' cognitive abilities and the limitations of traditional intelligence tests in capturing a comprehensive understanding of a child's learning potential. Referencing prior research, it explores the concept of dynamic assessment (DA) as a promising yet underutilised alternative that focuses on a child's responsiveness to learning opportunities. The paper highlights the potential of novel technologies, in particular tangible user interfaces (TUIs), in integrating computational science with DA to improve the access and accuracy of assessment results, especially for children with communication support needs (CSN), as a catalyst for abetting critical communicative competencies. However, existing research in this area has mainly focused on the automated mediation of DA, neglecting the human element that is crucial for effective solutions in special education. A framework is proposed to address these issues, combining pedagogical and sociocultural elements alongside adaptive information technology solutions in an assessment system informed by user-centred design principles to fully support teachers/facilitators and learners with CSN within the special education ecosystem.

Keywords: augmentative and alternative communication; tangible user interfaces; human–computer interaction; special education; dynamic assessment; user interface design; user-centred design

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1. Introduction

Educational assessment strategies should reveal an individual student's level of knowledge and provide their teachers with the information—for example, identifying and targeting gaps—required to maintain a positive trajectory of accomplishment [1,2]. In this way, an opportunity is created for an individual student's instruction to be personalised and enhanced. An experienced teacher with requisite knowledge can act upon the results of such assessments and implement remediation to bridge any shortcoming apparent in what the learner knows [3,4].

Today, the dominant forms of intelligence test to determine educational placement remain static test formats, measuring only a snapshot in time of an assessee's performance. An example is the widely used Stanford–Binet Intelligence Scale, currently in its fifth edition [5–7]. Typically, no feedback is provided, and it has been determined that these instruments gauge what the subject "knows" with little or no information gathered on how the individual solved the problems set for them. Such standardised, static test formats—norm referenced and restricted to one assessment point bereft of feedback—yield little or no evidence of *how* a child solves a problem set for them or what support they need from others (or from their environment) to learn [8]. The presumption here is that the testee fully apprehends the task or challenge before them and can respond unencumbered by personal traits, impairments, or sensitivities to give a rich and accurate picture of their abilities and potential [9]. For many (additional examples include minorities from culturally/linguistically diverse populations [10])—and in particular the focal population of this paper, young emerging aided communicators with communication support needs (CSN), who may be living with motor, cognitive, sensory and/or communicative impairments (for example, those with little or no natural speech and are consequently reliant on augmentative and alternative communication (AAC) solutions—addressed in more detail in Section 3.3.2 below—in their interactions with others)—this presumption can be flawed at best [11]. In fact, for an array of subjective reasons explored in more detail below, it skews the accuracy of such tests to the extent that the results are simply invalid as a predictor of learning potential—with implications for the child's pedagogical support that may prove deleterious and long lasting [12].

Dynamic assessment (DA), pioneered by researchers such as Budoff [13]; Feuerstein, Rand, and Hoffman [14]; and Campione and Brown [15], has shown much promise as a means of circumventing the uncertainties introduced by a traditional static test approach [8,16,17]. Broadly, it sets out to achieve this by leveraging integrated training to more accurately assess a child's responsiveness to a learning opportunity, rather than asking what they have learned before [9]. However, to date DA has seen limited uptake, and therefore impact, upon the practices of clinicians and educationalists [18,19]. As an approach, effective DA administration is thought to be more time-consuming and therefore costly to execute, requiring additional assessment points, sophisticated mediation (in this context, mediation refers to the manner in which a teacher, for example, curates their learner's journey, inspiring pedagogical growth by tailoring and reinforcing exposure to new concepts under careful and personalised supervision), and an extended focus on support [20]. This is a domain and predicament that seems well-placed to benefit from the careful application of emergent technological/computational advances.

A number of studies have sought to exploit the automation, data curation, and interactional advantages of an array of computer science technologies to mitigate the impacts of the constraints described [9]. One area of research, both more broadly in the field of human–computer interaction and within the particular niche of DA has been tangible user interfaces (TUIs—see Figure 1, p. 3 below) [8,21,22]. These access approaches apply the use of real-world objects that have been digitally enhanced, for example, with electronic sensors (e.g., Radio Frequency Identification (RFID) tags to enable location tracking) and multimodal feedback mechanisms (e.g., a mix of sound/vibration/LED lights or other status indicators to allow customisation and inclusive support for users living with different sensory, motor, and/or cognitive impairments, as children with CSN commonly experience). This may be applied to facilitate system control and manipulation with a corresponding reduction in the demand for users to master fine motor skill or to synthesise abstract representations as traditional computer graphical user interfaces with a keyboard, mouse, and screen typically do.

For these reasons, alongside novel opportunities for data capture, analysis, and generative output, TUIs may have significant advantages when integrated into a DA system for use by children with CSN, boosting vital access and accuracy of results. However, research to date in this area has also focused largely on the automation of DA to include computerised mediation with limited emphasis on the human element that may be an essential part of any effective solution [11,18,23]. In particular, learners with CSN are often living with comorbidities that exacerbate their sensitivities to this aspect [24,25].

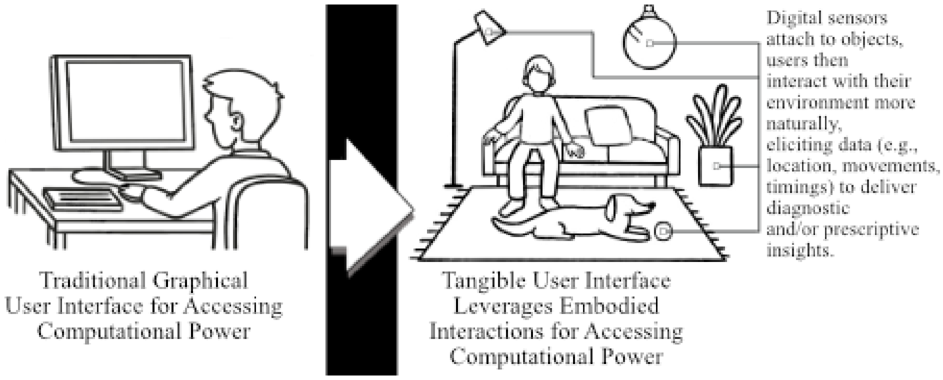

Figure 1. TUIs foster a more natural, interactive environment as an interface, promising significant potential access benefits for users who may struggle with traditional computer interfaces.

This paper, therefore, seeks to review the problem space from the perspective of fully supporting both teachers/facilitators, and young learners with CSN, within the special education ecosystem—with an overarching goal of calibrating the delivery of an effective (personalised) education for all that may boost the development of critical communicative competencies [26–28]. There is a particular emphasis on exploring three key, sometimes sharply contrasting, elements of this domain—the technological, pedagogical, and sociocultural domains—and considering a practical framework that might inspire a more seamless conflux of these towards a more harmonious whole that can potentially deliver important longitudinal benefits of DA to this community. The intention is to explore what happens when learners' functional impairments (motor, sensory, communicative) are mitigated effectively or removed, and they are provided with enriched and accessible cognitive stimulation. It is hypothesised that this may be the only way to appropriately assess what individual children with CSN are capable of.

2. Aims and Method

This section describes the aims and method used to conduct this review. The aims were as follows:

- Through a narrative review, summarise the advantages and disadvantages of DA in comparison with static assessments to establish a baseline for innovation and improvement.
- As an integrant of Feuerstein et al.'s mediated learning experience (MLE) [29], furnish an overview of the potential application (and gains) of technology-enhanced DA solutions, exploring the constellation of user-centred access methods, sensors, and wireless communication standards that might comprise such a tool.
- Building on the first two aims, explore system requirements for a robust DA psychometric test battery leveraging computational power, metrics and accessibility affordances. The goal is to deploy within the context of a practical framework that acknowledges and reflects embedded sociocultural exigencies. This aim will be framed and navigated via two broad themes of inquiry:
    1. How might human facilitators work in symbiosis—e.g., mediation–with sensor-powered, computerised elements of the system?
    2. How might current DA conduct and output (e.g., access, task-setting and report preparation) be enhanced or supported by such a system?

2.1. Method and Rationale for this Research

Research into the advancement of DA as a meaningful tool in special education implies that its uptake and significant potential advantages for child learners with CSN remain largely untapped [18,19]. Reasons for this are complex and manifold in accord with many challenges in this domain [16], and—as this review will posit—may require a holistic understanding and multi-faceted solution to be instituted for fruitful progress to be achieved.

2.2. Review Approach

A hybrid literature review approach was adopted for this paper, consisting of the following complementary tiers. These were:

1. An exploratory interrogation of numerous of databases (Google Scholar, Medline, PsycInfo, PubMed, Scopus, Web of Science) for titles, abstracts, and keywords of peer-reviewed papers, applying Boolean logic and wildcards for search terms, e.g., (child* OR adolescen*) AND (dynamic assessment) AND (CSN). These search terms were refined iteratively, with supplementary terms brought into focus—informed by initial paper reviews—and subsequently included where appropriate. For example, as the impact of limited uptake of DA came into sharper focus, the role technology might play as an empowering catalyst gathered momentum. Keywords in the search strategy were adapted to reflect this, e.g., ("computer* dynamic assessment" OR "dynamic test*").
   Exclusion criteria that applied were:
   - Grey literature (information sources that are divergent from traditional academic publishing and/or distribution channels);
   - Articles where full text was unavailable;
   - Articles in languages other than English.
2. A parallel collation of key prior peer-reviewed papers and other academic sources shared between the authors of the current review and further informed by authors' attendance of workshops run by, or based upon the work of, published DA pioneers and practitioners (Feuerstein, Tzuriel, etc.).
3. An augmentative "snowballing" search strategy was also deployed (following up bibliographies of references, and serendipitous discovery). This approach has efficiency benefits with acknowledged results in discovering resources that may be otherwise overlooked [30]. The "Cited By" functionality of the online service Google Scholar was also used to boost the search and retrieval of relevant papers beyond the database interrogations described above.
4. Filtering of candidate papers was cumulative, with first titles followed by abstracts and finally full-text screening taking place to reliably determine the pertinence of texts contributing to this review.

Review Results

In aggregation, this multi-faceted approach elicited a total of 156 candidate papers. The "snowballing" search strategy infused adaptability into the investigation as a whole, yielding constructive results that positively influenced the direction taken as the review unfolded. Recursive screening resulted in a bank of resources, split between two broadly dominant themes (Figure 2, p. 5):

1. Pros and cons of current approaches to the cognitive sciences in education, including both traditional and dynamic assessment batteries (n = 93).
2. Universal design solutions for the assessment domain that may enhance access and boost appropriateness of results (n = 63).

Publication dates spanned the years 1978–2023 inclusive, with the substantive majority (n = 95, or 70 percent) being published post-2010.

Jointly, the outcomes of this mixed search and collation strategy were comprehensive data robustly summarising the field, and spotlighting gaps in the research corpus, as detailed in the following sections.

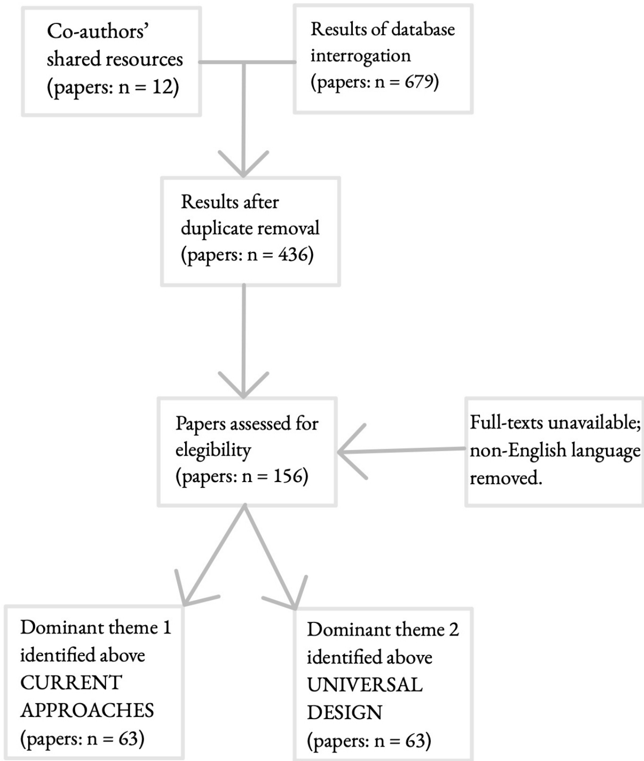

Figure 2. Resource search meta-analyses flowchart.

3. Narrative Review Outcomes

Based upon the articles reviewed, a distinction is made between traditional assessment (Section 3.1) and dynamic assessment (Section 3.2). The description of DA is further distinguished between more general theories and ideas and DA in clinical practice (Section 3.3). The particular relevance of DA for learners living with CSN and barriers to uptake are also explored.

3.1. Traditional Psychometric Assessment

Learner diversity and subjective experience (for example, situational impairment [31]) means that without due diligence and perhaps a modicum of good fortune, any static test format testee is at risk of underperforming and hence presenting with assessment results that do not divulge or represent their true potential. Consequently, a teacher working to prepare an individual education plan/programme (IEP) informed by those results may assign the wrong or ineffective domains for targeted support, with significant ramifications for their students' pedagogical outcomes. This dilemma is particularly confounding in the cases of individuals unlikely to fit a norm-referenced profile. For example, students from culturally and linguistically diverse backgrounds are unlikely to perform optimally if questions infused with local cultural mores or references are posed [10]. A simple example might be left-to-right cognitive biases determined by western orthography, and therefore not reflected in those from Hebrew or Arabic backgrounds. Similarly, children who experience anxiety in unfamiliar situations, have attention, behavioural, or sensory processing difficulties or motor impairments, will struggle to achieve within the context of a time-limited, one-off evaluation—in particular, when that test is administered by a stranger [12]. In the case of children with CSN who may use augmentative and alternative tools and strategies to communicate, there is clearly an additional layer of complexity not conducive to a brisk psychometric testing procedure [12,32]. These real-world issues represent a significant obstacle to the implementation of fair testing practices and the capture of accurate results that will enable educators to tailor the most effective pedagogical programmes for a notably vulnerable demographic.

In simple, normative terms: Practitioners would not choose to assess a preschool neurotypical child by challenging them to write an essay about their pet dog, on the basis that they are not typically equipped with the tools (functional literacy [33]) to undertake such a task. Some older children in that age group may have rudimentary knowledge of the alphabet or they may be able to write down their dog's name or draw a picture. However, such children are unlikely to (and it would be counterproductive to expect them to) mark (i.e., annotate orthographically or otherwise) their paper in such a way as to provide a full and complete record of their knowledge of that topic. Such an assessment would yield data about their stress responses to insurmountable tasks but would not be representative of their level of familiarity with the family pet.

A CSN communicator, for example, living with cerebral palsy, grappling with fatigue, cumbersome assistive technologies [23], and fragmentary support faces a broadly equivalent predicament. In juggling with competing detrimental pressures, their scoring in a traditional test scenario may bear little relationship with what they know (children with CSN face a multiplicity of obstacles that often impact their capacities to gain the same benefits from social, experiential, or formal learning interactions as neurotypical children do) nor provide any insights on how they approach problem solving [8,34]. Any teacher subsequently plotting an instructional trajectory for this student would be wise to regard such results with caution, with high risk of underestimation of the learner's potential and an IEP that neither reflects their abilities nor meets their needs [18]. This deficiency in the "one size fits all" efficacy of traditional assessment approaches, undermining the predictive validity of such tests for a significant and mutable minority of students, has fuelled the development of dynamic assessment in education [8,19].

3.2. Dynamic Assessment

A fundamental contention of DA is that the evaluation of a student's learning potential is as informative—and perhaps even more accurate as a predictor of their development and abilities–as current performance. This notion is grounded in the work of early 20th century psychologists such as Selz (who first recognised the pedagogical significance of a shift from "poor" to "good" errors [35]) and the sociocultural theories of Vygotsky [36], in particular that DA can be instrumental in creating his zone of proximal development (ZPD), a means of identifying and exploiting learners' emergent but yet imperfect cognitive functions [17,37]. Transcending the reactive essence of traditional tests, this asserts that a child learns actively, relying on a more knowledgeable other (MKO) such as a parent, peer, or teacher to guide them to the next (proximal) developmental level. The child acquires skills and knowledge with the support of scaffolding, recasting, prompting, and building on assessment-derived insights from their skilled communication partner, and this assisted performance pushing the cognitive boundaries until knowledge is internalised (and generalised) [16]. Engaging in this "inter-psychological activity" (Vygotsky's description [36]), the learner may advance from an incapacity to undertake an allotted task, through a very critical ZPD in tandem with MKO support, to the position where they have mastered the skill or task and can thereby undertake it independently. Designated the zone of actual development (ZOA) by Vygotsky, this latter position is also effectively the evaluative limit of classic static assessment methods, which, as explained above, may undervalue a child's potential if assessed in isolation and applying normative standards arbitrarily [18]. Navigating a child's growth from their ZOA—through the ZPD, and thereby beyond—is accomplished via the IEP (Figure 3, page 7 below).

In conventional DA, the MKO role is typically undertaken by the assessor. A key focus is to foster kinetic interactions with their subject, actively targeting their emerging rather than established cognitive traits, attempting to gauge the dichotomy between the learner's solo versus their supported task performance in order to inform and shape an evolving pedagogical trajectory [37]. This is framed (in practice, Vygotsky speculated upon [17], but never himself published, concrete techniques to achieve these outcomes) as a collaboration between the assessor and the child, with the former responsively calibrating the level of support the latter requires, as revealed by prognostic observation of their assessee's responses to prompting. This process invites synchronicity by the child, through active engagement, also gleaning insights that may benefit them in the future understanding of their own learning style and needs.

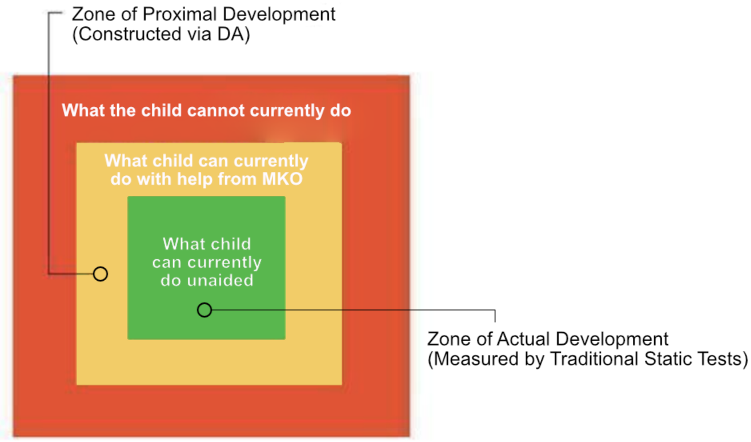

Figure 3. Vygotsky's Zone of Proximal Development.

This relationship between the MKO and the child learner is also mirrored in Feuerstein's student-centred mediated learning experience (MLE) [29] where the author refers to "human interactions that generate the capacity of individuals to change, to modify themselves in the direction of greater adaptability and toward the use of higher mental processes" [38]. This is underpinned by Feuerstein's theory of structural cognitive modifiability which acknowledges plasticity in ways of thinking and posits that development in cognition may be positively influenced by a holistic, active engagement with the learner [39,40]. This concept presents as a very progressive pedagogical philosophy with clear implications for nurturing potential educational achievements in individuals, regardless of their circumstances, with the requisite bespoke IEP and responsive mediation. This is a prospect particularly welcome for children with CSN, often living with conditions such as intellectual and developmental disabilities as well as motor and/or sensory impairments (children with CSN frequently remain marginalised, and potentially—if unofficially—deemed "uneducable" in clinical practice, despite the advent of inclusivity legislation around the globe in recent decades. This is clearly at odds with a basic tenet of the MLE that every human being has the potential to learn and grow). DA has been recognised as a key mechanism in gauging a learner's cognitive modifiability, utilising teaching and mediation strategies emerging from the MLE [20]. Childhood has been described as the developmental stage when the "advantages of MLE have the greatest impact on cognitive development" [41]. Deutsch illustrates a generic MLE interaction, which revolves around a pedagogic task tailored to the student's learning goals, as shown in Figure 4, p. 8 below.

The overarching goal—and a key factor of convergence with DA noted in the aims stated at the beginning of this paper—is to establish a clear understanding of the learner's current competencies and be able to use that understanding to formulate an approach to assist the child's learning. Within the context of the classroom, when a child is presented with a particular task or activity, the teacher will have an idea of what they are intending that the child will learn; in doing so they need to take account of the child's starting point. The teacher must also carry out an analysis of the activity in terms of knowledge, understanding, skills, and cognitive functions (cognitive function is a broad term referring to the mental processes involved in knowledge acquisition, manipulation of information, and reasoning, and includes the domains of perception, memory, learning, attention, decision-making, and linguistic faculties [42]) needed to carry out the task.

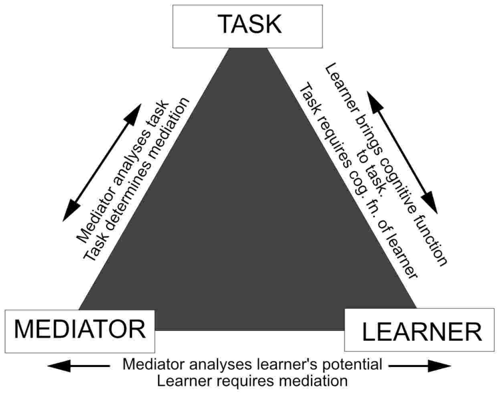

Figure 4. Adapted from Deutsch [18].

In practice, the teacher observes how the child approaches the task without intervention in the first instance. In one dominant DA model (see section *DA in Practice Today* for a deeper exploration of the diversity of approaches in the field), the teacher then adopts a range of graduated prompts (defined below) to mediate the child's learning; these prompts can range from repeating instructions, providing non-verbal cues like pointing, to carrying out the task jointly with the child. The teacher carefully observes how the child responds to the prompts provided. According to Deutsch and Reynolds [43], such interventions are "highly responsive to individual needs and lead to diagnostic and prescriptive insights that are uniquely relevant to a particular child".

A key focus of the current paper is the evidence prior research presents that DA strategies and mediation techniques may be superior for gaining insights into the cognitive potentials of children from an early age and that through the creation of such an optimal learning environment—building on knowledge gained through DA of individual students' attention, perception, working memory traits—better pedagogical outcomes may be achieved.

3.3. DA in Practice Today

Elliott describes DA as an "umbrella term used to describe a heterogeneous range of approaches that are linked by a common element, that is instruction and feedback are built into the testing process" [44]. An abiding tenet in contrast to static tests, according to Kozulin, is that "DA shifts emphasis on assessing the process of reaching the solution both quantitatively, i.e., the number of trials, and qualitatively, i.e., the strategy used, the type of errors" [17]. DA thereby provides a means "to understand the child's problems, how to work with a child, what the child may be able to do, or what the real needs are" [45]. Recognising the potential advantages for vulnerable groups, the two most prominent historical approaches, Budoff and Friedman's [13] and Feuerstein's [46], both emerged in the 1960s as attempts to mitigate the negative effects of static testing on populations operatively unsuited to, or ill-served by, that format. Children from socially deprived backgrounds, and those with special needs such as CSN, remain key beneficiaries [47] of the DA approach as a means of countering inaccurate or deprecative conclusions of potential where "missing" cognitive skills are absent through disadvantage rather than any inherent inability to acquire them [48].

DA approaches have been associated with coordinating the developmental stages of childhood—congruent with the benefits of the MLE described above—with numerous instruments targeting specific domains [49]. Campione and Brown [15], and Lidz and Thomas [50] both investigated applying their methods with neurotypical learners as young as four years of age, with the latter targeting the metacognitive processes (e.g., logic, deductive reasoning, and self-regulation) that emerge from between the ages of three and five years. The Bayley III DA diagnostic instrument, calibrated for children aged from one month to 42 months, has been successfully adopted with infants [51]. Further, Hessels' Analogical Reasoning Task (HART) was designed, and has been implemented, as a means of gauging the learning potential of children living with intellectual disabilities with very positive results demonstrated in predicting test outcomes contrasted against static alternatives [52]. In the field of communicative disorders, DA has been used to accurately predict reading level outcomes [53] and to discern diagnoses of disability from linguistic, situational, or cultural causes of performance limitations [54]. Furthermore, prior research by both Snell and Boers supports the applicability and benefits of DA for children (and older learners) living with CSN [55,56]. Notable here too are the contributions of Tzuriel and Klein, who co-authored the Children's Analogical Thinking Modifiability Test (CATM) [57] and the Frame Test of Cognitive Modifiability (FTCM) [58]. Tzuriel also created the Children's Inferential Thinking Modifiability Test in 1990 [59]. These three build on Feuerstein et al.'s ideas of structural cognitive modifiability and the MLE, leveraging aspects of their Learning Potential Assessment Device (LPAD) [60] via practical activities that appraise the testee on inferential or analogical problems of ascending complexity (for example, comparing or classifying the respective dimensions and colours of a variety of tangible, three-dimensional shapes).

A strength of DA is its adaptability and predisposition towards calibrating for assessees' individual needs and circumstances (personalisation) [61]. A broadly consistent DA approach, adhered to by many practitioners, is a familiarisation phase reviewing the activity to be undertaken followed by a test/teach (or intervention)/re-test format designed to yield data about the level of intensity and type of mediation required by the student to cultivate progress in the efficiency of their performance. A key part of this "sandwich" procedure [18,49] relies on the judgement of the examiner, who must act and respond sensitively to their subject's needs, supplying neither too little, nor too much, support. The level of time, skill, and experience required to oversee DA effectively is a significant disadvantage when contrasted with traditional static testing formats. Nevertheless, for children that normative test formats persistently misrepresent (such as those with CSN) and who might benefit from iterative, tailored, and, consequently for them, more effective intervention practises, such investment would seem invaluable.

For clarity, a generalised summation of the learning or instruction phase of a generic DA process as it might be executed is shown in Figure 5 (page 10). Note the simplified format, intended to illustrate one possible iteration of DA: The "Begin Task" step, for example, refers to the task identified in Figure 4 (page 8). This alone may be a complex, tailored element incorporating the expertise of the mediator (and potentially a wider inter-professional team) in identifying and targeting cognitive function, level of assistance required, and adaptation of the instruction and environment to suit an assessee's requirements (e.g., provision and calibration of access supports such as TUIs and AAC solutions).

This is a transactional representation of an underpinning DA intervention phase. From a more sociocultural perspective, mindful of the gains to be made from sensitive execution of DA (the *raison d'etre* of this assessment technique), sessions will be iterative, with probing engineered to elicit the most accurate data, dynamically adjusted according to the assessee's carefully monitored responses and needs.

For example, the mediator may commence a test aiming to initially present easier items that the child can accomplish without any assistance. This is intended to boost the child's confidence while gathering evidence of their problem solving strategies. Diagnostically, this is a much richer source of data pertaining to their cognitive functionality than classifying a proffered solution as correct (or otherwise). With the latter, an answer may be arrived at correctly via a flawed strategy, leading to failure when that strategy is applied to a more challenging item, possibly impacting on future efforts. In DA, mediation opens opportunities for discussion in selecting the most appropriate strategies or solutions, which in turn may equip the child with the tools to solve more challenging problems later as the complexity is escalated.

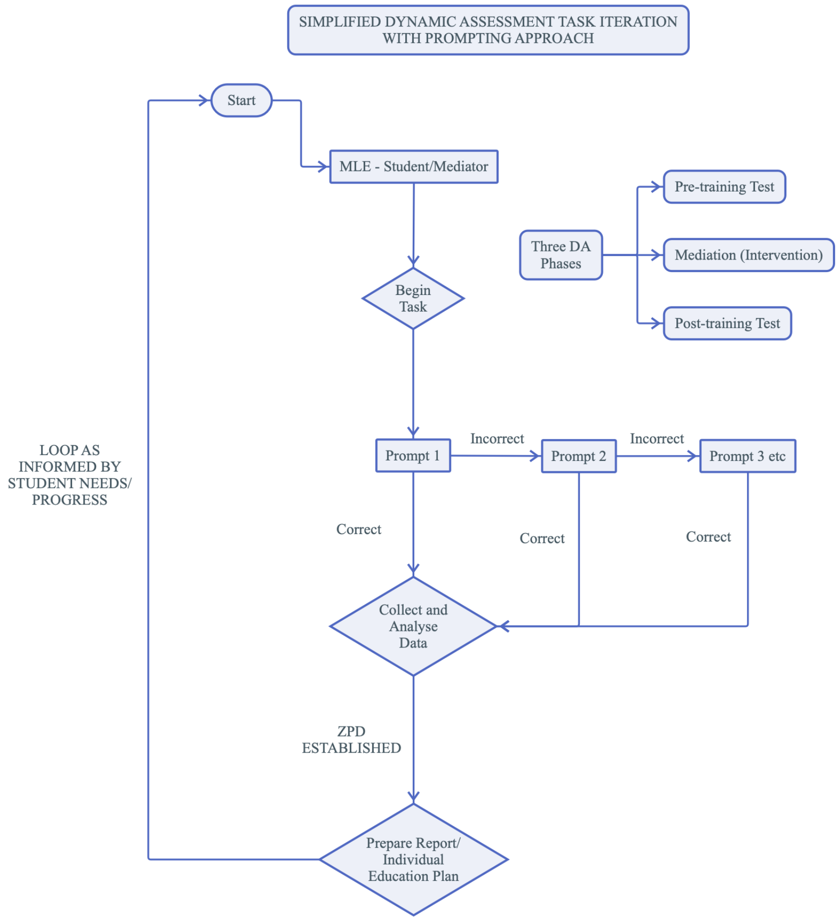

Figure 5. Exemplar DA Learning Phase Flowchart.

Numerous practitioners have described their recommendations for the overarching DA approach. Deutsch collated a comprehensive table of 17 DA models established through prior research showing significant overlap in terms of detail, with deviations being predominantly evidenced during the intervention (mediation) phases [18]. She synthesised these to document four distinct trending DA structures:

> "(i) A pre-test and post-test (note some researchers have advocated removing pre- and post-test elements to "reduce the time required to implement DA" [62]—further evidence of the need for streamlining DA administration that motivates this research) + Standardised Intervention; (ii) A pre-test and post-test + Graduated Prompts; (iii) Adaptive Testing using computerised tests with an intervention phase, but no personal interaction. (iv) Mediational Approaches: individualised; intervention is not pre-determined."

Building upon Lidz's ideas on the MLE, Jitendra and Rohena-Dias [63] outlined the following approach:

1. Pre-test and post-test activities (to enable the gauging of gain scores [62]), personalised to meet the needs of individual students, absent prompting or other assistance, to establish the learner's ZOA.
2. A learning phase utilising materials that reflect and reinforce those used in the pre- and post-testing.
3. The adoption of mediation techniques commensurate with those proposed in the MLE by Feuerstein et al.

Multiple, or hybrid, approaches to DA are commonplace [62]. In the foregoing, the heterogeneity described by Elliot [44] may be seen, and it also may be seen that mediated learning techniques are both pivotal as a means of "revealing the underlying metacognitive processes that facilitate learning" [64] and the dominant locus of divergence.

3.3.1. Graduated Prompting

Numerous studies have utilised graduated prompting or hinting to structure mediation of activities of children with CSN (or otherwise disadvantaged learners) undertaking DA [15,65–69]. This mediating technique was initially created to evaluate variance, quantitative and/or qualitative, in the cues or instruction required by a child testee tasked with solving a set problem (or series of problems) successfully. The "graduated" portion of the appellation refers to the needs-based (mediator-escalated or de-escalated, responsive to circumstances) progression of cues as informed by close observation of a testee's levels of performance [8]. Due to the prognostic insights DA seeks to gain, these prompts are typically ordered in a hierarchy described as "least to most" (referring to the degree of mediator intrusion deemed necessary for the testee to complete a task successfully). Cues might therefore progress from generalised metacognitive hints to firmer cognitive scaffolding (also described as generic versus directed prompts [70]) and ultimately to sharing or explaining a strategy that will assist the learner to reach the correct solution. For example, having left space and time for the child to begin a task unaided, the mediator may initiate verbal instructions, perhaps increasing in intensity and augmenting with gestures such as pointing, following this with partial/full modelling before advancing to physical guidance/joint task execution if and as required. Adopting a hierarchical prompting sequence in this way yields important data that a skilled practitioner can synthesise to ascertain a learner's current status and future support needs for improvement. By scoring mediation interactions [71] (for example, the nature and number of cues necessary to complete a task [72]) a more accurate—and therefore utilitarian—assessment, reflecting the child's cognitive modifiability, may emerge than can possibly be captured amidst the "noise" and intensive scrutiny of a static, summative interrogation [16]. In this context, blurring the boundaries between assessment and instruction, a more effective, user-friendly pedagogical model may be forged that is geared towards fairness and enhanced support for those vulnerable groups most negatively affected by traditional assessment techniques.

Table 1 below provides an illustrative example (aimed at assessing the cognition domain) of graduated prompting within a mediated learning environment.

Table 1. Graduated Prompting Exemplar.

Matching Activity (Targeted Domain–Cognition)
Goal: Learner can discern between similarities and differences. Materials: Cards, photographs, artefacts/objects where two are identical. Cognitive Functions: Perception; labelling; relationships; elimination/selection. Key Terms: Together; more; other; also; same; different.
Approach:
1. Place cards, pictures or objects face up on the table. Do this in such a way that you gain the learner's attention. Start with three pictures, two the same and one different. 2. Prompting procedure: Following each step, pause and allow the child time to interact. a."There are three items here, two are the same. Can you put them together?". Point to each item in turn. b. Point to one item: "This is a. . . (name item). Which item is exactly the same? Which item belongs to this? Which item looks just like this? Where do you see another?". If the child chooses correctly, ask why these are together? (The object is to identify and understand their problem solving strategy). c. Move your finger slowly to the correct answer. And model: i. These two are exactly the same. ii. They are both. . . (provide name)/they both have. . . (name their common attributes). iii. This one is different. . . (point to the other item and explain how or why it differs).

For clarity, graduated prompting is not promoted here as an indispensable part of DA. As noted in the section above, there is no universal protocol for the administration of DA, nor would such a protocol necessarily be beneficial.

3.3.2. DA and Its Benefits for Learners Living with CSN

A defining feature of the otherwise heterogeneous grouping identified as children with special needs might be the inapplicability of many normative pedagogical procedures and approaches. As such, they are particular potential beneficiaries of DA, as highlighted in the section *DA in Practice Today* above. For those with CSN, the focal population of this paper, the personalisation that is integral to DA comes into even sharper relief [72]. Many children with communicative impairments will have recourse to strategies or tools that aid them in their communication, the branch of assistive technology known as augmentative and alternative communication (AAC), introduced briefly earlier in this paper. These tools and strategies encompass a wide range of techniques, running the gamut from no-tech (e.g., on-body signing) to low-tech (e.g., card- or perspex-fabricated E-Tran frames), to high-tech (e.g., electronic supports such as speech generating devices). Ideally, these are carefully calibrated to meet the individual's needs. In this, a parallel may be detected with the DA approach that makes compatibility with this diverse group of learners apparent.

Young AAC users with CSN may be living with congenital disorders such as cerebral palsy, autism spectrum disorder, or Down's Syndrome or may have acquired their disability later through illness or a traumatic event (e.g., locked-in syndrome). It is common for individuals to have an array of tools or strategies in place for use in response to the situational diversity of daily life. For example, a CSN-aided communicator who uses a speech generating device attached to their wheelchair in most circumstances may switch to sign language or a communication board when in the bath or laying on a play mat.

It remains a common experience for people living with CSN to be marginalised, underestimated, misdiagnosed, or otherwise misunderstood [73,74]. Because of their communication difficulties and/or compromised ability to control their movements, those without intellectual disabilities may be assumed to have such an impairment; those with a mild intellectual disability may be identified incorrectly as having a more severe impairment. Additionally, such presumptions or misinterpretations are not restricted to the general public. It remains challenging even for professional clinicians and teachers to define how disabled a child diagnosed with profound and multiple learning disabilities actually is (and whether their diagnosis is accurate). Clearly, this situation contributes to the difficulty of assessing individuals accurately for the most effective constellation of AAC supports for their needs, and to their prospects for developing autonomy and independence in life–a situation recognised, and intended to be addressed, by the approach of presuming competence [75]. A common, though understandable, response to endemic levels of poor or late diagnosis and underestimation is for individuals with CSN to become passive, or adopt "learned helplessness", further contributing to their marginalisation. Thus, those with CSN remain a highly vulnerable—and complex—group of learners to educate and support. This is exacerbated because—even in those all too rare instances where diagnosis and, where appropriate, personalised AAC support for their impairment has been administered early enough [76]—the tools and strategies these learners then adopt present another layer of complexity for the facilitator of a traditional static test to see beyond [77,78]. It follows that any IEP based upon such an assessment runs a particular risk of being unsound.

The advantages to be gained from DA for these students represent a significant levelling of the playing field. Multiple assessment points facilitated by a skilled MLE practitioner, part of a team around the child who have considered any new vocabulary requirements for the test and provided for them in a format best suited for that learner (be that on an aided language display, speech generating device, communication board, or specific signs/gestures) deliver an opportunity to dramatically reduce stressors, and thereby record more representative results. A pre-test session allows for the DA mediator and the aided assessee to collaboratively ensure that any language deficits, cognitive or other operational/access challenges may be prepared for and mitigated against.

3.3.3. Barriers to Uptake of DA

Thus far, the preponderance of evidence appears to demonstrate that the perfunctory constraints of standardised testing set a significant proportion of (arguably the most vulnerable) learners up for failure. We should entertain no illusions about just how potentially debilitating such lost opportunities can be for prospective pedagogical, and concomitantly, sociological, and fiscal outcomes, nor can or should the requirements of anti-discrimination legislation around the world over the past half-century (e.g., Section 504 of the Rehabilitation Act 1973 in the USA; UN Convention on the Rights of Persons with Disabilities 2006 [79]; Equality Act 2010 in the UK) be ignored.

And yet, as indicated in the introduction to this paper, uptake of DA by practitioners is limited to an extent that is inevitably damaging for many children who could benefit from the improved targeting of pedagogical support that it might deliver, but for whom it remains frustratingly out of reach [18,19]. The literature suggests there remain legitimate logistical barriers to wider traditional DA access, including the following:

- Advanced level of administration/mediation expertise required [8,18].
- Capture and synthesis of high volumes of complex data [8,16].
- Demands of multiple assessment interventions [80].
- Increased time/effort requirements related to the above, especially when contrasted with static testing and the number of hours typically available to practitioners in the field [18,81].

These barriers may be seen to apply across all populations of potential beneficiaries of DA, but may be particularly egregious and requiring of sensitive handling for learners with CSN. For example, knowledge of (or added inter-professional support towards) sophisticated assistive technologies may add still further demands to the level of administrative expertise required. Similarly, accommodating multiple interventions may be more taxing for this complex population of learners, as in any activity requiring engagement with others in their lives. Therefore, it is essential that novel ways of administering DA that mitigate these types of stressors should be explored.

Assessing the barriers listed above, it is reasonable to conclude that traditional DA is a task-based, resource-hungry endeavour and an iterative one characterised by the accumulation of data sets for analysis to identify patterns and qualitative adaptations. As in many other domains where efficiencies in data capture and manipulation are sought, one potential means of democratising DA is by exploiting computational power, automation, and technology-mediated learning techniques [70,82]. The addition of high-tech AAC technologies to this mix also represents a use case where enhanced access opportunities may multiply the benefits for aided communicators, as explored in the following sections of this paper.

4. Computer-Assisted DA

Semiconductor technologies have advanced dramatically [83] since Lidz declared in 1991 that the "potential for computerization of [DA] is quite limited", citing the levels of expertise and clinical judgement this diagnostic assessment approach demands [64]. In the three decades since, a series of investigators have explored this avenue of research, conducting studies with a diversity of child participants, across a range of ages and abilities in an effort to overcome the barriers outlined in the section above. A broad unifying rationale underpinning these efforts has been to maximise and improve the opportunities for DA by transferring or sharing responsibility for certain tasks to the silicon chip, with divergence manifesting largely in the balance of human agency vs. computer automation. In other words, the focus remains upon familiar DA/MLE procedures (e.g., observing adaptations a testee exhibits that might indicate their cognitive modifiability; following a pre-teaching, teaching, and post-teaching sequence of phases; incremental offering of problem-solving strategies (mediation) during the intervention phase), while integrating a continuum of evolving computational power to support or achieve these objectives.

Hence, we see Zhang et al. develop a successful computer-based graduated prompting assessment with a dynamic graphic interface to "foster perceptual intuition" [70]; Passig et al. experiment with a 3D immersive virtual reality environment and the MLE to test young children's analogical reasoning (and describe creating an ""intellectual partnership" between computer, mediator and child) [20]; Touw et al. leverage the portability of a tablet computer to administer DA (a "dynamic series completion test") in the classroom with primary school age learners [80]; and researchers such as Verhaegh et al. and Resing et al. establishing evidence of the advantages of electronic tangibles—tangible user interfaces (TUIs) that rely on sensor-equipped physical objects to capture and digitise user activity at high granularity—over screen-based computer-assisted DA, in tandem with automated (computerised) mediation [21,84].

Figure 6 below summarises the position of computerisation nested within a traditional DA hierarchy, with some examples of technology and tools (not intended to be exhaustive) that researchers have utilised in their contributions to the field.

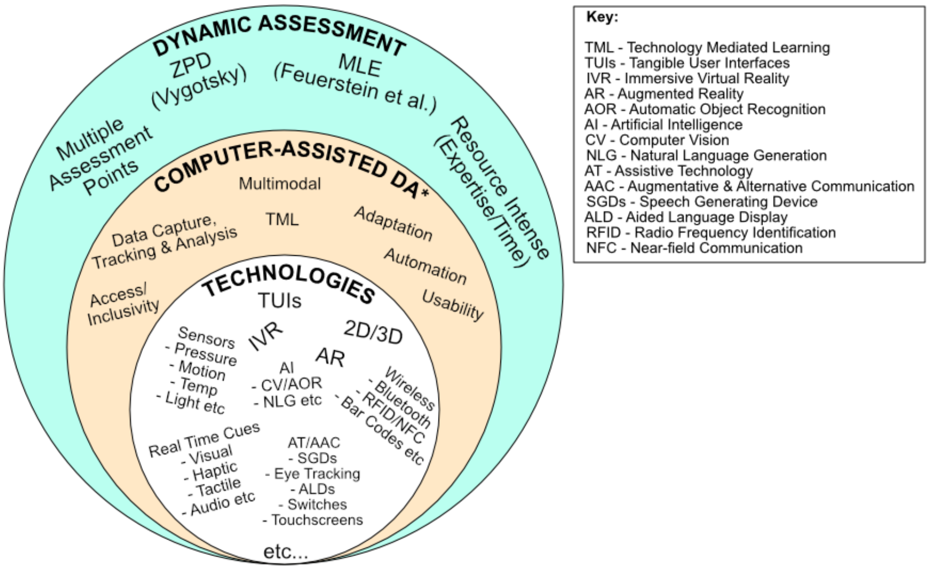

Figure 6. Computer-assisted DA Hierarchy.

4.1. *Personalisation and Access Affordances of Digital Technology*

Digital technology influences every facet of modern living. Certainly in industrialised societies (and increasingly beyond), the vast majority of citizens carry a powerful multimedia, networked, and camera-equipped computer in their pockets wherever they go in the form of a smartphone. In the field of AAC and CSN, the advent circa a decade ago of consumer-oriented touch screen devices with dynamic displays and their accompanying app stores dramatically multiplied opportunities for access to high-tech assistive tools such as speech generating devices—many of them shared on a decentralised (open source) software development model. Simultaneously, artificial intelligence-infused technologies such as computer vision, natural language generation and processing, eye tracking [85], and speech recognition have proliferated, revolutionising our capacity to empower users living with disabilities such as CSN. Engaging, responsive, adaptive, multimodal, and connected, the user-managed automation that these cumulative technologies represent promises to deliver agency into the lives of people with CSN undreamed of only a few years ago.

No two prospective CSN communicators are alike, and it is this blend of multimodal adaptability that allows digital technology to map so favourably to their disparate needs [21]. Suitably assessed, a mix of solutions optimised to match the user's needs may be devised to provide the best possible support for them.

Furthermore, it is acknowledged that while some children with CSN may find traditional graphical user interface (GUI) computer access paradigms (With WIMP (windows, icons, menus, pointer) for control, and separate 2D computer monitor) too abstract or otherwise inaccessible [18,86], others, for example those with autism spectrum disorder, often value the precision and predictability of computer-based interactions, finding them less intimidating and consequently more stimulating than interactions with people [23,87]. In a similar vein, the potential for injecting fun and engagement into the assessment process, for example by introducing the motivational affordances of gamification, should not be underestimated on a high-resolution, multimedia-equipped device or platform calibrated to accept user commands, and deliver captivating responses, across the spectrum of sensory modalities [11,22,88,89].

With this in mind, the projection of such technology into the assessment field represents a natural and logical continuity of approaches. As in other areas of a CSN communicator's life, the indications are that sensitively applied, technology-supported assessment can deliver enhanced access, and thereby testing practices, geared towards—rather than contrary to—promoting fairness, recognition of an assessee's disability, and enhancing the accuracy of test results.

By combining the power of technology with DA, it may be possible to overcome the obstacles faced by individuals with CSN through the following:

- Enhancing their access to stimuli;
- Enabling optimal processing;
- Providing them with accessible response modes.

The outcomes of such assessments—adapted through technology to accommodate each disabled learner's individual needs—could thereby optimise their developmental progress.

4.2. Tangible User Interfaces (TUIs)

Traditional, or analogue, DA tasks or items vary dependant on the core domain being targeted or assessed. For example, inductive reasoning has been recognised as a key element of a child's pedagogical and cognitive development, assessable through activities such as seriation, categorisation, and analogies [8,90]. A common strategy is to use physical objects or artifacts—such as an assortment of wooden geometric-shaped blocks—to set a child challenges such as discerning where they match or differ and prompting them to order or move the objects to demonstrate their level of comprehension. This is an approach taken in much of Tzuriel's influential work on traditional DA, cited earlier in this paper. Conducting such tests, the facilitator must be at pains to mediate with skill and close attention to the timing and nature of their testee's movements, and their (conscious or otherwise) semiotic cues—complex data that are challenging to collect competently [84].

Despite these difficulties, the advantages of designing pedagogic activities around the use of physical (tangible) objects are compelling [91].

Piaget's theories of knowledge acquisition in childhood posit a number of developmental stages [92,93], with sensory–motor stimulation—interactions with objects in the real world—being intrinsic and vital, a view supported by numerous postliminary researchers [94]. Similarly, Vygotsky also viewed learning through engagement in tactile, physical interactions as an important ingredient influencing child development [36]. Others have concurred [95], including later researchers such as Reid and Schaefer [96], who investigated and promoted the therapeutic possibilities of physical interactions within game play, with fun and playfulness being another recognised catalyst towards skills and knowledge acquisition, most notably in the pioneering work of early 20th century educator Maria Montesorri [8,97]. The link between perception and cognition appears clear [19,95], with Verhaegh observing that the "manipulation of objects can support the child in constructing mental representations of the world around him or her, and in creating knowledge about physical events" [22]. The reason for this may be the advantages three-dimensional forms can offer in constructing knowledge through cumulative modes of information, stimulating additional senses such as proprioceptive perception in a way that less modally-rich materials such as "flat" 2D visual representations cannot [95]. Tangentially supporting this thesis, the reinforcing attributes of multimodality are of well-established benefit to communicators with CSN in particular [98,99]. In the wider population, a highly relevant example of the innate learning and problem solving advantages of tactile engagement is the way that children instinctively use their fingers to assist them in basic arithmetical calculations such as adding and subtracting numbers [100]. In sum, perhaps spurred by our evolutionary needs as corporeal actors within a four-dimensional ecology, the opportunity to manipulate real-world objects, exploring their relationships, may work at a visceral level to lower the cognitive demands on us and deliver insights in learning or problem-solving situations.

Combining these affordances of physical objects with those of the digital technologies discussed above is a logical next step, and one that over the years has been taken by numerous researchers in the fields of DA—and more broadly in human–computer interaction—to create what have been monikered as graspable [101] or tangible user interfaces (TUIs) [102] that can potentially grant or enhance access to computational power (bits) even for previously marginalised groups of users [98,103]. These introduced the concept of attaching (the majority of systems incorporating sensor technologies involve the attachment of low-cost sensor modules wirelessly linked to processors, but some have bypassed this requirement—Google's ATAP Project Soli, which has been utilised to apply sensitive radar to interface design, is one example [104]) one or more networked sensor technologies (see Figure 6, on page 14, elaborated for object tracking technologies in Figure 7 below) to physical objects, thus creating taggable, trackable "electronic tangibles" [8] or "digital manipulatives" [105], to forge "computationally-mediated interfaces that more seamlessly weave together the physical and digital worlds" [106].

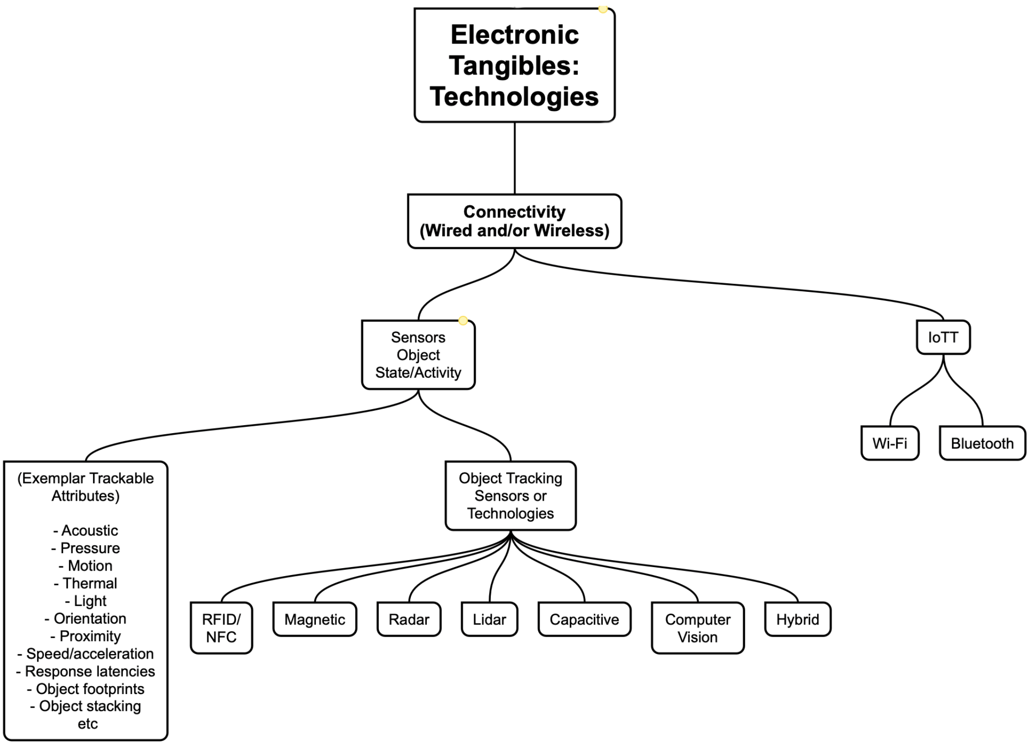

Figure 7. Object tracking technologies.

Exemplar TUI Technologies Investigated in Prior Research

The diversity of approaches and technologies deployed by prior researchers exploring TUI systems is reflected in some key examples collated in Table 2 below (a few of which are briefly expanded upon in the paragraphs below).

Table 2. Collected exemplars of object tracking technologies.

RFID/NFC:	Spielberg, A. et al. [107]; Hsieh, M. et al. [108]; Hengeveld, B. J. [98].
Magnetic:	Hwang, S. et al. [109]; Liang, R. et al. [110].
Radar:	Yeo, H. et al. [104].
Lidar:	Lee, H. et al. [111].
Capacitive:	Chan, L. et al. [112]; Voelker, S. et al. [113].
Computer Vision:	Jafri, R. et al. [114]; Avrahami, D. et al. [115].
Hybrid:	Villar, N. et al. [116]; Liang, R. et al. [117].

We see an array of techniques, manifested individually or in combination. However, recurring themes are the novel potential of TUI systems and the unique, practical advantages that leveraging tactual stimuli via such an interface might deliver in a plethora of domains, including the instructional, gaming, clinical, and pedagogical domains. There is a particular emphasis on TUIs as social/collaborative tools, multimodal and rooted in the real world with affordances beyond the 2D virtual reality of traditional systems.

Working with passive RFID tags, Spielberg et al. [107] valorised their affordability and utility (wireless, batteryless, low-latency) for building interactive games (for, example, Tic Tac Toe, and Pong) with trackable pieces.

Also utilising RFID technology, and of particular relevance for this paper's demographic focus, Hengeveld [98] developed a play-based TUI system to boost language learning in children with CSN. This modular system was designed with a comprehensive suite of tangible input materials, aimed at providing maximum flexibility in adapting to individual users' needs, alongside a facilitator-operated controller for targeted prompting and support.

Yeo et al.'s [104] experiments with short-range radar (using an electromagnetic signal to detect objects, in this case Google's Project Soli sensor [118]) demonstrates the potential of tracking any real world object's size, position and rotation without modifying the target. This allows any object to become part of an interactive user interface without the adaptations required by other systems (for example, the attachment of sensors). Combined with machine learning, the team was able to create educational board and card games with generic components.

Lee et al. [111] explored the use of Lidar (infrared laser technology) to build a multi-user/multi-touch immersive virtual reality (VR) TUI system, on a room-sized scale (this development, built around a system called CAVE [119], has also been described as "mixed reality" [120]).

Jafri et al. leveraged computer vision—the AI-powered acquisition, processing, and analysis of digital images—to develop a system with 3D-printed objects which children with sight impairments can use for learning about geometric shapes [114]. Automatic object tracking and recognition via digital cameras has become a significantly more powerful technology in recent years, with competing algorithms from major vendors such as Google, Amazon, and Microsoft. For tracking purposes in a TUI, lighting conditions and occlusion may be problematic [116].

Finally, Villar et al.'s [116] Project Zanzibar developed a hybrid system, combining near-field communication (NFC—a short-ranged wireless technology, evolving from RFID) and capacitive sensors to deliver a very flexible TUI that allows the accurate detection of object location, orientation, stacking, and footprint combined with audio- and screen-based user feedback. They used this to create augmented reality (AR)-enriched interactions in a variety of games, educational spelling activities, and Montessori-inspired exercises.

This preceding research and literature—cumulatively leveraging the inherent strengths of IoT (IoT is an acronym for the Internet of Things, a term used to describe networked and/or embedded physical objects equipped with sensors or processors [121]; Angelini et al. suggest this might usefully be expanded to IoTT (Internet of Tangible Things) for the current context [91]) computational power, allied with play- or task-oriented three-dimensional objects—reveals a potentially transformational mix of access, usability, automation, and analytical opportunities that builds a persuasive case for infusing these tools and techniques into assessment praxis. Auspiciously, many of the attributes noted also resonate with well-established advantages of traditional DA, that is, delivering more robust support across culturally and/or physically divergent populations as well as the neurodivergent population [98]. Tables 3 and 4 (below), detailing attributes of analogue/digital systems, respectively, are intended to summarise many of these benefits, again as exemplified by the work of prior researchers.

Table 3. Potentially Beneficial Properties of Non-electronic Tangible Interactions in DA.

Analogue Tangible/Graspable Objects
Grounded in theory: Tangible interactions are clearly congruous with dominant theses of child development regarding sensory engagement espoused by Vygotsky, Piaget, etc. [122]
Intuitive: High ecological validity exploits lived experience and real world human skills [103]
Reduced learning curve: Easier/faster to learn and understand for children, e.g., perceptual affordances of control linked to representation; immediacy of proprioceptive feedback; directness of interaction [8]
Predictability and control: Deliver continuity/persistence of information, e.g., continuous presentation of objects of interest; reversible actions (facilitates trial and error problem solving); resistance to errors such as power outages [103]
Facilitate collaboration: Shared interaction space means multiple access points; enables responsive mediation [91]
Security: Enables/encourages emotional attachments to be exploited, e.g., familiar (user-friendly) objects such as a learner's own toys can be utilised [91]
Multimodal: Offers enhanced access to multiple modes of connection, e.g., tactile features reduce or eliminate dependence on visual attention and screen time [91,123]
Fun: A natural promoter of playful learning/gamification [122]

Studies that have explored computer-assisted DA typically maintain the MLE and pre-teaching/teaching-intervention/post-teaching "sandwich" phases that characterise many models of this assessment approach, and predominantly report positive outcomes involving a variety of settings and subjects. Themes vary from the simple use of tablet computers for assessing pre-school CSN communicators [72] through the utilisation of immersive virtual environments to test first- and second-grade students [20], but the extensive potential benefits of TUIs have arguably been at the forefront of many of these investigations. Of particular note in this domain is the work of Resing and affiliated academics in the Netherlands. A common theme of these studies has been exploring the potential automation benefits accruing from computerised or synthetic mediation and scaffolding. Table 5 (on page 19) is an attempt to collate key studies in a pedagogical environment blending cognitive test battery systems with electronic tangibles support.

Table 4. Potential Added Benefits of Electronic Tangible Interactions in DA.

Added Value of Electronic Tangibles
Engagement: Amplifies stimulation through the addition of multimodal feedback mechanisms. This trait also multiplies the adaptive potential of any test battery system, essential for meeting the needs of a diverse demographic of users [95]
Scalability: Potential of automation to mitigate the barriers of time and labour that traditional DA administration requires [80]
Data curation: Diversity of sensors and wireless connectivity offers the opportunity to gather and analyse previously unavailable mass data (e.g., tracking of object movement, orientation, proximity, 3D space, response latencies, etc.), thereby gaining/synthesising insights for DA report [9]
MLE: Computer mediation/electronic scaffolding may offer efficiency/standardisation gains [84,106]
Personalisation: Adaptive control and feedback mechanisms, e.g., eye gaze, offer wider opportunities of access and usability [124]
Signalling: Perception through physical embodiment reduces necessity of screen time in any computer-assisted test battery system [116]
Flexible: In theory, almost any physical object—including familiar objects belonging to the testee—can become a part of a computerised TUI by temporarily attaching modestly priced sensor technologies such as RFID tags [116]
Richer interactions: Although touchscreens have been shown to be intuitive for young users, tangible manipulation has additional benefits such as haptic feedback [91]

Table 5. TUI in Prior DA Research.

TUI in Prior DA Research				
Researcher(s)	**Mediation**	**Tool(s)**	**Test Focus**	**Outcome**
Veerbeek et al., 2019 [8]	Synthetic	TagTiles	Series completion task	Positive
Resing et al., 2011 [84]	Synthetic	TagTiles	Graduated prompting	Positive
Resing and Elliot 2010 [16]	Synthetic	Tagtiles	Dynamic testing via TUI	Positive
Verhaegh et al., 2013 [122]	Gameplay	TagTiles	Cognitive testing via gamification	Positive
Xu 2005 [103]	N/A - User/self	Generic/IoT	General	Positive
Resing et al., 2017 [90]	Synthetic	TagTiles	Grouping Answer Pieces (GAP)	Positive
Verhaegh et al., 2013 [11]	Synthetic	TagTiles	TUI tasks v nonverbal IQ tests	Positive

The studies reviewed in Table 5 were almost exclusively positive about outcomes arising from their application of a TUI access solution; for example, one concluding “superior predictive qualities (arising from) dynamic testing for school performance compared with static testing” [8]. However, there is also a distinct lack of diversity in the TUI computer systems deployed, perhaps as a result of the limited options available for commercial TUIs based upon graspable physical objects (as opposed to augmented reality or projector-based systems [103]). TagTiles emerges as dominant in the literature, a TUI-based educational games console by a company called Serious Toys (or, latterly, Symbio Therapy) that tracks objects on its A3-sized surface using RFID sensors, providing synthetic (speech) feedback and mediation through sounds and coloured LED lights. Serious Toys (www.serioustoys.com (accessed on 7 September 2023)) appears defunct at the time of writing, their last tweet was shared in 2012, and they are unresponsive to email contacts—although research involving their product can be found from as recently as 2018.

In sum, the multimodal, and thereby inherently adaptive, traits of TUIs appear to offer compelling potential benefits for enhanced engagement and inclusion in the implementation of DA to support young learners living with CSN. The physical learning environment such interfaces provide can stimulate any and all of the user's senses, allow practitioners to oversee individually tailored, collaborative engagement (e.g., age-/environment-/impairment- or AAC-appropriate engagement) and thus support a child's development via prompt, targeted, and enriching feedback when engaging with assessment-oriented tasks and concomitantly informed clinical/pedagogical planning [125].

4.3. Alternative Candidate Technologies and Approaches

We should be clear that the application and testing of novel alternative access methods, a bellwether focus of the overarching field of HCI, is a highly significant factor in assessing requirements for any technology-augmented tool or system. Given the user group this review aims to support, this is also a critical aspect of the current paper's focus. However, the practical application, the maturity of the technologies under scrutiny, their adaptability, and the likelihood of fruitful symbiosis with extant or emerging systems or resources (be they organisational, human or digital) must also be considered.

4.3.1. Immersive Learning Systems

At the beginning of Section 4 above, this review documented a selection of examples of prior work leveraging computers to enhance DA practice. Of these, perhaps immersive technologies such as virtual and/or augmented reality (VR/AR) represent the most promising novel alternatives "rivalling" TUIs in terms of disruptive potential. VR technologies "operate by constructing computer-generated environments that mimic the human experience through auditory, visual and tactile feedback" [126].

The general pedagogical advantages for learners of immersion (differing virtual learning simulations have varied degrees of immersion, with VR at the top and augmented reality (AR) representing the lower end of the scale, although potentially offering similar benefits—the authors regard a full comparative analysis as being beyond the scope of the current paper) within such a digitally enhanced setting are potentially numerous: allowing users to experience diverse perspectives, boosting situated learning, and enhancing transfer from the classroom to the real world [127]. These strengths are underpinned by social constructivist theories of learning [128].

As we have seen, Lee et al. [111] developed an immersive VR system that also incorporated a TUI. In another approach, with a specific DA focus (referenced earlier but expanded here), Passig et al. worked to develop a computerised version of Tzuriel's CMB Analogies test [20]. This could be operated using a traditional 2D GUI or as an immersive 3D VR application via a head-mounted display. The goal was to "enable the subject to feel as if s/he is part of the environment... to present abstract concepts and novel points of view which cannot be presented in this way in the real world". This facility was deemed "empowering" in the DA context, in terms of assessing analogical reasoning skills.

These are certainly areas worthy of further study, as the cited papers' authors' conclude. Bryant et al., reviewing the potential of immersive technologies in the wider field of communication disabilities, agree they can be "useful", both for supporting learners with CSN, and for teaching health professionals best practice in the domain [126]. They caution, however, of some barriers that might exist, particularly affecting users in this demographic. For example:

- Ethical concerns
  - Psychological stress may be induced in virtual scenarios for vulnerable individuals.
  - Privacy and data protection vulnerabilities.
- Safety concerns

– VR experiences have the potential of inducing motion sickness.
– Noise and repetitive strain risks.
– Cyberbullying on online platforms may be exacerbated in VR worlds.

Bryant et al. concluded that, while promising, VR research and application in speech-language pathology remains in its "infancy".

4.3.2. Brain–Computer Interfaces

Brain–computer interfaces (BCI) are an emerging (BCIs have been "emerging" for some decades [129] and are becoming increasingly viable and effective but remain limited in their distribution/availability [130]) access technology that detect changes in brain activity and utilise computer algorithms to analyse and decode patterns with the intention of interpreting thoughts, words, intentions or user commands [131,132]. They come in both invasive (implanting a device directly into the user's brain) and non-invasive (e.g., typically using surface electroencephalogram (EEG) sensors attached to a user's scalp) formats for signal acquisition [130]. They have been variously deployed for controlling on-screen cursors, virtual keyboards, AAC technical tools, prosthetic devices, wheelchairs, gaming consoles [133], and even as a "high-performance speech neuroprosthesis" [131] (and many more applications).

However, as with immersive technologies (and perhaps even more pronounced), there remain ethical, legal, social, safety, and security concerns, particularly in the case of invasive BCIs [130]. For the purposes of this review and its target demographic, there are also added complexities in the efficacy and application of this technology upon younger (and still developing) brains [132]. The atypical brain anatomy of those with congenital impairments and the paucity of research conducted with children in this domain are examples of these drawbacks [133]. Nevertheless, research shows children can demonstrate control and task execution, contingent upon "strategy, task and age" [132]. Furthermore, this interface access method—in whatever form—must remain a compelling candidate for delivering autonomy and participation to the most profoundly disabled children, such as those living with locked-in syndrome [134].

In sum, while there appears both significant promise and prominent technical and ethical obstacles to surmount in developing BCIs further, for some users, the benefits may outweigh any costs. The authors found no examples of prior research combining BCIs with DA, and this may be an omission warranting further exploration.

4.3.3. Summative Reflection of Candidate Technologies

Beyond the research already discussed, evolving digital/AI innovation means that a cornucopia of potential operational adaptations now present, from unimodal to multimodal interface configurations and additional sense-specific sensor technologies (e.g., speech recognition [135], speech synthesis [136], and natural language processing [137]), avatar technologies [138], tutoring systems, and performance logging and analysis algorithms (see Section 4.4 below). Applying a user-centred configuration of some mix of these tools, computer-assisted tutoring systems now have great potential to support adaptive learning, utilising different types and degrees of prompting, shaping, and automation. The evidence suggests that harnessing these technologies effectively presents an opportunity to revolutionise DA and enthuse users (both practitioners and assessees), thereby amplifying its accuracy, reach, and impact. It is worth emphasising the synergy often observed resulting from the effects of adopting multi-faceted solutions as we see in numerous of the foregoing references in this review, such as Lee et al. [111]. This hybridity is a recurring thread in any solution-focused search for the most apposite and efficient design and is ideally arrived at via engagement with end users, i.e., user-driven. The responsiveness required in real time of (and inherent in) the system to accommodate adjustment to a specific user's needs will inform the complexity of the solution. For illustrative purposes (in practice, BCI adoption would require training in advance of any assessment session, but this illustration of the articulated, nested attributes that may be required of any needs-based solution stands), an elaborate hypothetical example might be the introduction of a non-invasive BCI that empowers a child living with CSN to control a robot arm for manipulating a TUI as part of a dynamic assessment test battery system. Those may be the requisite provisions that allow that individual child to participate in a DA, and combined with sensitive facilitation, make progress towards achieving their full potential.

This example also highlights that no technical access or pedagogical solution is likely to be perfect, and all may have their relative strengths and weaknesses. It follows that no single solution should be ruled out as a potential contributor to any DA test battery system nor ruled in to the exclusion of others without a user-focused rationale having been sought and established.

That said, the foregoing evidence also leads the authors of this paper to propose that TUI-empowered systems—in the short to medium timeframe—have fewer ethical issues and great practical application and utility for the user group(s) targeted in this paper. Therefore, they present a compelling case for inclusion, either in part or in whole, as a candidate technology for user-centred development within the stated context of this review.

4.4. Leveraging Data Synthesis and AI to Boost DA

As long ago as 1988, Bunderson et al. identified four ascending generations of computerised assessment, culminating in what they termed "intelligent measurement (IM)" which they defined as "producing intelligent scoring, interpretation of individual profiles, and advice to learners and teachers, by means of knowledge bases and inferencing procedures" [139]. This references exploiting the unique automated logging and number-crunching strengths of computational power to inform tailored interventions by revealing prognostic details of the decision tree pathways of students undertaking assessment tasks, a highly significant overlap with the tenets of DA. In the literature, the TagTiles system described earlier appears to output precisely the types of logged data, beyond a simple binary record of task outcomes, to enable such inferencing procedures, e.g., completion time per task; time elapsed between each move towards solving a problem; number of moves required; and number and types of prompting required [16]. However, in the literature these logs seem to have been primarily employed to demonstrate the efficacy of the computerised TUI under investigation (for example, by contrasting outcomes of those using the test system against control groups) rather than to, at least partially, automate collation of an individualised DA report—important IM functionality which must be a key goal or requirement for any system geared towards promoting wider-scale access to the benefits of DA.

In 2015, Greiff et al. noted a stagnation in research on computer log files in pedagogical assessment and that IM has not "come to fruition" [140]. They acknowledge the need for technical expertise, and despite the recent advent of techniques such as educational data mining (educational data mining is the application of data mining techniques to the analysis of data generated by educational systems, involving the use of machine learning and statistical techniques to identify patterns and relationships in data related to student learning, motivation, and behaviour), "it is often difficult to give conceptual meaning to and to derive specific implications from the behavioural patterns found" [140]. As a result, the full rewards and opportunities represented by computerised assessment have remained elusive [8]. It would seem essential to disrupt this hiatus or stagnation in research to develop tools that can exploit the obvious potential of computational power in this area. In line with other general trends in AI, the collection of big data—in this context accumulating large volumes of evidence inferring the nature of a child's problem-solving processes—has become increasingly optimised, while the corresponding analytical tools for this domain have not kept pace.

Nevertheless, it is well established that pattern recognition is a strength of artificial intelligence and machine learning algorithms [141]. AI systems are designed to identify patterns in data which can be used for a wide range of applications such as image and speech recognition, natural language processing, and—crucially here—predictive analytics.

In general, pattern recognition involves analysing data to identify regularities or trends and then using those patterns to make predictions or decisions. Computer systems equipped with AI algorithms are particularly good at this task because they can analyse large amounts of data quickly and accurately, and they can "learn" and adapt over time as they encounter new data. For example, an AI system might be trained to recognise patterns in images and classify them based on those patterns. It could be used to identify objects in an image, classify the image as a particular type of scene (such as a beach or a city skyline), or even identify specific individuals in the image. Similarly, an AI system should be able to be utilised to recognise patterns—quantitative and qualitative—in the movement and timing interactions of a student manipulating a TUI-equipped DA test battery to complete a set task. This appears to be an area ripe for development in advancing computer-assisted DA and may be the key to distributing access far more evenly in special education.

4.5. Summarising Potential Computer-Assisted DA Gains

The predicament confronting current uptake of DA may be expressed as low scalability versus the needs of sizeable, diverse populations, and their stakeholders, desperate for meaningful, tailored assessment mechanisms. On the foregoing evidence, in addressing the bulleted reasons for this identified in the section on *Barriers to Uptake of DA* above, there appear to be major contributions that computational power can make to this domain, that currently remain largely untapped. As a caveat, the authors again emphasise the intrinsic symbiosis of computational power with the human factor here; the former serving to assist mediation, enhance access, or otherwise multiply the efficiency of the latter, postulated as follows:

- Access
  - Scalability;
  - Adaptability and the enabling traits of tech (e.g., eye gaze, switches, voice control, BCIs);
  - TUIs/VR enrichments;
  - Intrinsic, established inclusivity benefits of multimodality;
  - Potential of online resource distribution/remote access.
- Expanded productivity
  - Benefits of careful integration of sensor technologies and AI automation into DA administration;
  - Ameliorating pressures from intensity of labour for facilitators or synergistic combination.
  - Reusability/repackaging strengths of digital resources.
- Engagement
  - Ease of customisation;
  - Stimulating/fun;
  - Multimodal;
  - Responsiveness/immediacy;
  - Tactility;
  - Immersion;
  - Enhanced transfer of knowledge.
- Data accuracy
  - Reduced user anxiety: this also applies to analogue DA but may be amplified further with access to the benefits of a tailored analogue/digital mix;
  - Capture and retrieval of rich user data critical to decision-making that may otherwise be lost.
  - Enhanced, evidence-based planning tailored to the individual learner's needs delivering gains in nurturing complex skills acquisition, e.g., communicative competence.
- Data tracking
  - All assessment is a data mining endeavour, the merit of which may be measured by its accuracy (see above);

  - Both quantitative and qualitative data sets;
  - Large data volumes becoming both manageable and determinative.
- Data synthesis
  - Major potential contribution to the vital output of DA: AI automation harnessed to streamline preparation of the user-centred report that will inform bespoke pedagogical measures.

5. Discussion

Children presenting with CSN, often with limited or no speech due to multiple disabilities, are typically not accurately testable with traditional, standardized tests. The literature provides evidence that dynamic assessment can make it easier to identify the most appropriate communication, developmental and learning support goals for each individual child. In DA, clinicians, teachers or parents work with the child to find the interventions and communication supports that best fit the child's developmental perspective.

With DA, facilitators pay attention to skills (that which the child can perform independently) and abilities (that which the child can and would like to be able to perform with help from the environment or with the help of more knowledgeable others). At the same time, they take into account the child's own way of perceiving, processing information, solving problems, and expressing themselves. They do not focus on what a child cannot do, but rather on what the child can or should be able to do, with or without help from the environment or communication support tools.

Grounding this discussion in the aims as originally stated in Section 2 above:

There is ample evidence emerging from the foregoing review about the respective strengths and weaknesses of static versus dynamic assessment techniques. The most urgent matter is the recognition of the reality that the former has potentially significant drawbacks in utility for delivering accurate predictive or diagnostic results for learners living with CSNs, with clear implications for their futures. The gains implicit in DA as an alternative approach are also highlighted extensively above, but with the caveats evidenced by restrictions in uptake we see to date arising from the elevated demands in both labour and practitioner expertise inherent in its implementation. DA offers potential that remains largely unrealised for this population to date.

Exploring the promise of technology-enhanced DA as part of a transformational solution has been a particular aim of this paper. Prior research in this area presents encouraging results, but the literature shows little evidence that this has led to the wider uptake that is required to make a truly significant impact.

5.1. Prioritising the Sociotechnical Balance

Efforts to streamline traditional (analogue) DA administration continue. Consider, for example, the Cognitive Abilities Profile (CAP) [142], whose creators described developing a consultative model in order to attempt to "address or bypass some of the barriers to greater use of DA" [18]. Many are disinclined to trust computers as a way forward, citing human mediation and expertise as key; Deutsch asserted that the requirements go far beyond simple test administration [18]. Haywood and Lidz emphasise the indispensability of specialised training and emphatically advocate restricting DA facilitation to experienced (human) professionals [61,143]. There is much to support such a thesis, but this should not preclude the adoption of technology to expedite DA procedures under the learned direction of experienced practitioners.

Antle observes that children are "active learners embedded in a physical and social environment" [100]. Note in particular that this dynamic, that social interactions in collaborative activities produce robust synchronisation between two participants' brains, was recently revealed in pioneering research using computer vision "hyperscanning", showing them functioning together almost as one system in cooperating [144]. The tangible and spatial interactions explored here do not occur in isolation, and thus their efficacy must be intrinsically linked with the motivational, emotional, and knowledge-constructing dynamics of human contact. The value and influence of the community within which any augmentative computer system must operate should therefore not be underestimated. Norrie describes any such solution as being "inextricably bound in the symbiotic relationships between hardware, software, community partners, policies and individual user attributes-a sociotechnical system" [145].

The challenge must therefore be to integrate the burgeoning strengths of computational power outlined earlier in this paper with the innate, nurturing synergies of human mediation, underpinned by a system interface primed for adaptation and responsiveness (a parallel field of study resonant here is that of affective computing in education, and there may be significant opportunities to exploit in DA here too, for example Wu et al. [146]) to the technological, pedagogical and sociocultural needs of the child undergoing assessment.

5.2. Towards a Future Technology-Enhanced DA Solution: Recommendations for the Field of AAC

This narrative review of DA, with its particular focus on young learners with CSN, presents a baseline of current practices. Critically, it also reveals significant prevailing weaknesses in the application of those practices where technical innovations, geared towards expanding opportunities for access to this more bespoke, responsive form of assessment, may afford real qualitative differences for a vulnerable demographic too often poorly served in this domain.

As discussed above, prior efforts to leverage computational power in DA have undoubtedly shown promise yet have proved frangible in terms of meaningful results, i.e., as apparent in reflecting that the majority of related studies have taken place some years ago with little or no subsequent evidence of wider uptake and distribution via the exploitation of computerised automation.

Considering the foregoing, what form might a novel—and above all practical and sustainable—balance of human/machine resources take to deliver the necessary support and mitigate or overcome the barriers identified in Section 3.3.3 of this paper? Three summative system requirements—here addressing the aims set out at the beginning of this review—proposed are as follows:

- Recognition of the value and maintaining the executive agency and protection of an embedded human element of reflective mediation and administrative support.
  - Procedures that enable responsive calibration and optimisation of human interactions are a feature, rather than a bug and are integral to any effective computer-assisted DA system.
  - The traits and sensitivities of the learner and the skills and intuition of the facilitator of any DA activity must remain pivotal.
- An adaptive, multimodal interface that prioritises access for all, particularly aimed at meeting the needs of learners with CSN.
  - The authors propose that a contextually flexile, TUI-equipped system holds significant, as yet untapped, potential as a candidate component within that sociotechnical mix of a computer-assisted DA solution.
  - Alternative technological solutions, considered in Section 4.3 above, currently appear less evolved—or more ethically problematic—to seamlessly integrate into the system under consideration in the short- to medium-term.
- An AI-synthesised set of metrics leveraging enhanced data captured by machine sensors to dramatically boost the productivity and complement the intuition of the skilled human facilitators DA so clearly needs to achieve wider distribution.
  - The literature indicates that the strengths of AI-powered computer automation have not been meaningfully leveraged to date in DA, and the potential deployment of this technology—again, in concert with vital human mediation and user-centred design—is a compelling prospect that warrants further investigation in the field.

Building a system capable of delivering accurate assessments and tailored, effective support to the heterogeneous mix of users educators must engage with—at the scale, speed, and frequency required—demands a flexible and nuanced approach. The literature demonstrates that key complementary elements of the technology, clinical and pedagogical practices that are or could be in place, could be used in tandem with the induction of a more cohesive framework with a focused effort to harness the AI. Therefore, the potential of achieving a disruptive solution that transcends current limitations is significant, extending access to DA to those such as children with CSN who need that support most keenly.

We anticipate that such a sociotechnical-oriented system congruent with this architecture may deliver a DA test battery that resolves the obstacles identified in this paper and addressing the challenges of the interdependent trio of elements (technological, pedagogical, and sociocultural) we identify as underpinning this domain.

6. Conclusions

This review documents evidence that DA has a number of advantages over traditional static testing and (in its dominant analogue form) barriers, both in terms of administration and specifically in addressing the needs of the focal population, children living with CSN. Identifying novel pathways to leverage these advantages and overcome these barriers may be key to allowing this population the opportunity to develop greater communicative competency, and thereby flourish and lead fulfilling, more independent lives.

Over the course of this research, computer-assisted DA, particularly utilising the multimodal flexibility of TUIs, emerges as a candidate solution of great interest. The unique collaborative problem-solving strengths of DA activities powered by TUIs—be that through interactive storytelling, symbol or object matching, puzzles and games, etc.—demand further exploration, and yet research and adoption using these technologies in this domain appears somewhat stalled.

Practitioners, researchers, and the field in general must acknowledge that this is an area with massive potential gains but many complex hurdles remaining to be overcome. Not least of these is recognition of the need to devise systems and solutions that deliver a harmonic interplay between hardware/software/human intervention. To achieve this successfully will require user-driven technological innovations in concert with community inclusion, procedural adaptations and support. The challenge is significant, yet the technology is extant, if yet unharnessed in a form that can overcome the barriers and deliver the gains promised. The foregoing review highlights a sociotechnical balance of elements that the authors contend is both necessary and now feasible. Most importantly, delivering DA more widely by developing a responsive, computer-assisted system that delivers the optimal mix of requirements identified here may be the next step towards successfully providing children living with CSN with vital access to enriching pedagogical assessment support currently denied to them. In turn, the authors hope this can boost their access to more positive developmental outcomes, to their lifelong benefit, and to that of society as a whole.

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Abbreviations

The following abbreviations are used in this manuscript:

DA	Dynamic Assessment
TUI	Tangible User Interface
CSN	Communication Support Needs
RFID	Radio Frequency Identification
AAC	Augmentative and Alternative Communication
MLE	Mediated Learning Experience
IEP	Individual Education Plan
IM	Intelligent Measurement
ZPD	Zone of Proximal Development
MKO	More Knowledgeable Other
ZOA	Zone of Actual Development
VR	Virtual Reality
AR	Augmented Reality
NFC	Near-Field Communication
HCI	Human–Computer Interaction
GUI	Graphical User Interface
BCI	Brain–Computer Interface
AI	Artificial Intelligence

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