

Personalising wearable neuroimaging for neurodivergent children through co-design with families and industry

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Abstract

Wearable neuroimaging methods hold considerable promise for identifying early biomarkers of neurodevelopmental conditions, yet their application to neurodivergent young children remains limited by significant participation barriers. We investigated inclusion rates and parental experiences in a combined virtual reality and diffuse optical tomography platform. Fifty-four 3-to-7-year-olds across three groups, neurotypical, elevated likelihood of Attention Deficit Hyperactivity Disorder (ADHD/EL), and autism (Autism/EL, predominantly confirmed diagnoses) were tested twice. Neurotypical and ADHD/EL children engaged at consistently high rates, with near-ceiling task completion and equipment tolerance. Engagement in the autistic group was markedly more variable, shaped by equipment-related hypersensitivity, particularly the shutter glasses and the cap, that persisted across visits despite targeted adaptations. Parental insights corroborated these findings: anticipated and experienced equipment concerns differed significantly across groups and remained elevated for autistic families throughout both visits. Signal quality in the autistic group was correspondingly lower and declined between visits, partly attributable to cap loosening for more sensitive children. Drawing on iterative parental co-design and industry partnership, we developed a four-phase personalisation framework covering pre-visit preparation, in-session adaptations, and engagement with device developers. We provide the first evidence base for inclusive wearable neuroimaging in neurodivergent children and a replicable framework for moving the field beyond one-size-fits-all protocols.

Keywords Optical imaging · Neurodivergence · Inclusive research · Participatory research · Virtual reality · Wearable neuroimaging

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Introduction

Approximately 15% of the global population is neurodivergent, encompassing conditions such as autism, Attention Deficit Hyperactivity Disorder (ADHD), developmental language disorder, developmental coordination disorder, and learning difficulties^{1–3}. While in some situations there are visible signs during the first years of life, formal identification typically occurs later in childhood^{4,5}. Early identification and diagnosis open a critical window for intervention during a period of heightened neuroplasticity, with well-documented benefits for developmental trajectories and quality of life^{6–9}.

Initial investigations showed that neurotechnologies might hold considerable promise for identifying early biomarkers of neurodevelopmental conditions prior to any behavioural expression^{10–13}. For example, 4-to-6 months infants with elevated likelihood of autism showed decreased brain responses to social stimuli, responses which predicted autism diagnosis at 3 years^{14,15}. Moreover, reduced neural responses to tactile stimuli at 10 months of age have been shown to predict later autistic traits at 24 months in infants at elevated likelihood of autism or ADHD¹⁰. These advancements stand to substantially deepen our understanding of different developmental trajectories from very early on and inform early years intervention^{7,16}. More recently, interest has expanded beyond infants with elevated likelihood of autism or ADHD to include young children in whom early neurodevelopmental differences may be more behaviourally apparent^{17,18}. However, translating these early findings into reliable biomarkers remains a significant challenge. Neurodevelopmental conditions are characterised by considerable heterogeneity, both within and across diagnostic categories³, meaning that large, diverse datasets are needed to identify robust neural signatures. Acquiring such datasets is itself complicated by the fact that current neurotechnology protocols are frequently poorly suited to neurodivergent children, who may find the equipment, testing environment, or procedural demands difficult to tolerate^{19,20}. Addressing this fundamental participation barrier is therefore a prerequisite for the kind of large-scale, inclusive neuroimaging research that meaningful biomarker discovery requires, and it is this challenge that the present study directly addresses.

Common neuroimaging modalities impose significant physical demands on participants: electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) require the placement of tight-fitting cap, and functional Magnetic Resonance Imaging (fMRI) requires children to lie motionless inside a narrow, loud scanner bore for extended periods. For children with hypersensitivity, a profile common in autism and ADHD¹³, these demands can render participation distressing. Beyond the physical demands of wearable equipment, the procedural structure of standard neuroimaging assessments presents further barriers for neurodivergent children. Laboratory testing procedures for neuroimaging systems are often lengthy, requiring children to remain seated and cooperative for extended periods, penalising the natural movement and fidgeting characteristic of some young children. Excessive movement may introduce noise into data collection, which can affect overall data quality and inadvertently reduce the inclusion of participants with higher levels of hyperactivity. Similarly, many studies have excluded autistic individuals with intellectual disabilities²⁰, often because standard tasks require sustained attention to screens or strict rule-following that may not be accessible to these participants. Collectively, these procedural demands systematically exclude the children most likely to benefit from early neurodevelopmental assessment, and introduce selection bias that undermines generalisability, ecological validity, and the reproducibility of findings.

Virtual reality (VR) offers a promising avenue for addressing some of these barriers. By enabling precise experimental control within immersive, engaging environments that resemble everyday life, VR bridges the gap between traditional laboratory paradigms and naturalistic research²¹. Importantly, VR also allows a greater range of movement than conventional lab setups, making it especially suitable for toddlers and young children. Our VR setup has already been validated with typically developing children, showing positive outcomes in terms of participant compliance and data quality^{21,22}. Critically, however, VR also introduces its own participation challenges: the setup requires children to wear shutter glasses, adding to the overall equipment burden, and the immersive nature of the environment, while engaging for many, may itself be a source of discomfort or overwhelm for

children with hypersensitivity. Whether the benefits of VR outweigh these additional demands, and for which children, remains an open and empirically unresolved question, underscoring the need to systematically evaluate its suitability and accessibility across the full range of neurodevelopmental profiles.

It is essential that the developmental neuroscience community moves beyond a one-size-fits-all approach to assessment, and invests in the co-design and empirical evaluation of inclusive, adaptable testing protocols that can meet the needs of the full neurodiversity spectrum, particularly during the preschool years, when the potential benefits of early identification are greatest. To address this, we collaborated with researchers, our industry partner Gowerlabs Ltd., and families of neurodivergent children to tailor VR and wearable Diffuse Optical Tomography (DOT), one of the latest advances in optical spectroscopy, to better meet participants' needs. DOT provides high-resolution, three-dimensional reconstructions of brain activity and deeper penetration into brain tissue, offering functional imaging resolution comparable to fMRI^{23,24}. Recent developments have made DOT wearable, portable, non-invasive, and robust to motion artifacts, making it a promising tool for studying children's brain activity in more naturalistic settings²⁵, such as VR. In this study, neurodivergent and neurotypical children aged 3-to-7 years completed two sessions of a Go/No-Go inhibitory control task in the Birkbeck ToddlerLab CAVE (Cave Automatic Virtual Environment) virtual playground, wearing the LUMO wearable DOT system (Gowerlabs Ltd). Here participants were asked to pop only the blue bubbles (Go trials), while avoiding the red ones (No-Go trials). We recorded changes in blood oxygenation in the brain as an index of neural activation in the frontal cortex, as this region has been shown to be engaged during inhibitory control tasks in children of the same age²². Children with a diagnosis or higher likelihood of autism (due to having a first-degree relative with autism), children with a diagnosis or higher likelihood of ADHD (due to having a first-degree relative with ADHD), and neurotypical children were recruited to attend two testing sessions at the Birkbeck ToddlerLab. It is important to note that while the autistic group comprised predominantly children with a confirmed diagnosis, the majority of children of what here we define as 'ADHD group' were included mainly on the basis of familial history or current assessment rather than a confirmed clinical diagnosis, and should therefore be considered as a group enriched for ADHD liability rather than a clinically diagnosed sample. In this study, we use "neurodivergent" as a descriptive umbrella term for children with, or at elevated likelihood of, neurodevelopmental conditions such as autism and ADHD, adopted in keeping with the inclusive emphasis of the neurodiversity framework; as our participants are young children, the term is used descriptively and implies no assumption about self-identification. Our sample is best characterised as "enriched for neurodivergence": it includes children with a confirmed diagnosis, children with elevated traits or familial likelihood, and, by extension, some children who may ultimately follow a typical developmental trajectory. Sessions were spaced one to two weeks apart, enabling an iterative process of co-design and personalisation in ongoing dialogue with children, families, and Gowerlabs Ltd, our industry partner. Parents completed questionnaires after the first and the second visit, providing feedback on their child's experience and suggestions for protocol adaptation, to tailor the setup to each child's needs across visits and to assess children's engagement respectively.

The aim of this paper is to share valuable insights into participants' engagement with our testing setup, imaging data quality, and the personalisation process developed through dialogue with families and our industry partner. Although rarely documented in the scientific literature, this collaborative and adaptive process is fundamental to making developmental neuroscience more inclusive, transparent, and accessible. Based on the known sensory and attentional profiles associated with autism and ADHD, we predicted that: (i) engagement and equipment tolerance would be lower, and more variable, in the autistic group than in the neurotypical and ADHD groups, reflecting the higher prevalence of hypersensitivity in autism; (ii) DOT data quality would mirror engagement, with lower signal quality in the autistic group showing poorer equipment tolerance; (iii) engagement would improve across the two visits as children became more familiar with the testing environment and as personalised adaptations were introduced, regardless of the diagnostic group. Beyond these specific predictions, the documentation of the personalisation process itself, and the analysis of parental questionnaire and open-ended data, were approached as exploratory and descriptive. While the functional neuroimaging findings from this study are reported separately in a forthcoming publication, these findings will provide the first empirical framework

for optimising testing inclusion in neurodivergent young children, offering concrete, actionable guidance for researchers seeking to design more inclusive wearable neuroimaging testing set-ups.

Results

Before examining engagement and data quality, we confirmed that the three groups were comparable on key demographic variables. No significant group differences were observed in gender distribution, $\chi^2(2, N=54)=4.27$, $p=0.118$, or age, $F(2, 51)=0.775$, $p=0.466$, indicating that the Autism/EL, ADHD/EL, and neurotypical groups were well matched on these characteristics. Task performance is reported in full in the Supplementary Material. Accuracy on the Go/No-Go task did not differ significantly across groups or between sessions, indicating that task difficulty was broadly comparable and unlikely to account for the group differences in engagement reported below.

Participants' engagement with the testing set-up

Table 1; Fig. 1 summarise engagement with each component of the testing setup across both visits for the three groups.

Neurotypical group. Engagement was consistently high. All 23 children attended Visit 1 and completed the task; 21 returned for Visit 2, with attrition due to participants' personal circumstances. Task completion remained very high at Visit 2 (20 out of 21). Tolerance of all three equipment components, the motion-tracking glove, DOT cap, and shutter glasses, was near-ceiling across both visits, with only isolated instances of partial wear, due to a technical issue with the glasses (i.e. only one lens functioning correctly) rather than child refusal.

Table 1 Engagement with the VR-DOT testing setup across diagnostic groups and visits. Children's engagement with each component of the testing setup is reported for Visit 1 and Visit 2 within each group. Values represent the number of children engaging with each component for the full session, partially, or not at all, with percentages calculated from the number of children attending that visit. Partial engagement indicates that the component was worn or the task was attempted for only part of the session. * denotes instances of non-wear attributable to a technical issue with the shutter glasses rather than child refusal.

Measure	Neurotypical (N=23)		ADHD/EL (N=15)		Autism/EL (N=16)	
	Visit 1	Visit 2	Visit 1	Visit 2	Visit 1	Visit 2
Attendance & task completion						
Children attending visit	23	21 / 23	15	14 / 15	16	14 / 16
Completed task – full session	23 (100%)	20 (95%)	14 (93%)	13 (93%)	8 (50%)	9 (64%)
Partial engagement	–	1 (5%)*	–	1 (7%)	2 (12%)	4 (29%)
No engagement	–	–	1 (7%)	–	6 (38%)	1 (7%)
Motion-tracking glove						
Full session	23 (100%)	21 (100%)	14 (93%)	14 (100%)	12 (75%)	11 (79%)
Partial	–	–	–	–	1 (6%)	1 (7%)
Did not wear	–	–	1 (7%)	–	3 (19%)	2 (14%)
DOT cap						
Full session	21 (91%)	21 (100%)	13 (87%)	13 (93%)	10 (63%)	9 (64%)
Partial	2 (9%)	–	–	–	2 (12%)	3 (21%)
Did not wear	–	–	2 (13%)	1 (7%)	4 (25%)	2 (15%)
Shutter glasses						
Full session	18 (78%)	17 (80%)	14 (93%)*	14 (100%)	7 (44%)	8 (57%)
Partial	4 (18%)	2 (10%)	–	–	1 (6%)	1 (7%)
Did not wear	1 (4%)*	2 (10%)	1 (7%)*	–	8 (50%)	5 (36%)

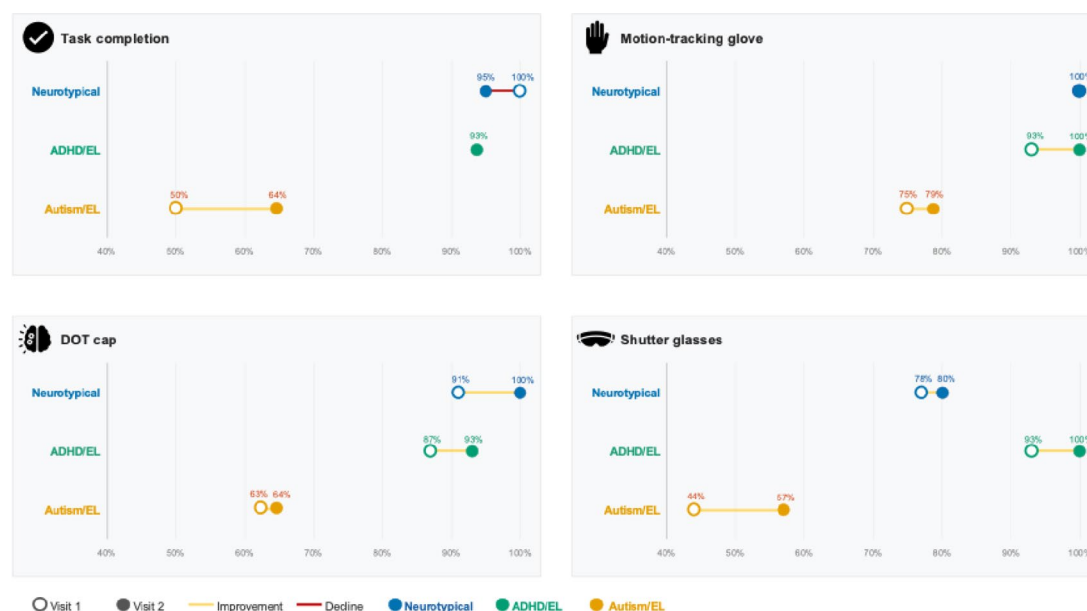


Fig. 1 Graphical representation of the full-session engagement with each component of the VR-DOT testing setup across groups and visits. Each panel shows the percentage of children achieving full-session engagement with a given component of the testing setup (task completion, motion-tracking glove, DOT cap, and shutter glasses). Neurotypical group is represented in blue, ADHD/EL group in green, and Autism/EL group in orange. Open circles represent Visit 1 and filled circles represent Visit 2. Connecting lines indicate the direction of change between visits (yellow = improvement, red = decline).

ADHD/EL group. Engagement was also high and broadly comparable to the neurotypical group. 14 of the 15 children completed the task at Visit 1, and all 13 out of the 14 who returned for Visit 2 completed it (the parents of the only child who did not return for Visit 2 did not provide a reason for not returning to the lab). Equipment tolerance was similarly strong, with full-session wear of the glove, DOT cap, and shutter glasses observed in the large majority of children across both visits.

Autism/EL group. Engagement was markedly more variable. Of the 16 children who attended Visit 1, only 8 completed the full task, 2 were partially engaged, and 6 showed no engagement. At Visit 2, attended by 14 children, 9 completed the full task (2 of which had shown partial engagement in Visit 1), 4 were partially engaged (all of which had shown no engagement in Visit 1), and 1 showed no engagement. Among the two children who did not attend Visit 2, one missed the session due to a family matter, and the other due to lack of engagement in Session 1. Equipment tolerance was also low: shutter glasses were the most challenging component, with 8 of 16 children not wearing them at Visit 1. Tolerance of the motion-tracking glove and DOT cap was higher, with 12 of 16 children wearing the glove and 10 of 16 children wearing the cap for the full session at Visit 1. Equipment tolerance was very similar for Visit 2.

Because some participants reported discomfort with the cap, particularly with the chinstrap, this was removed to minimise distress for 3 children in the Autism/EL group at Visit 1 and for 2 children in the Autism/EL group and 1 child in the ADHD/EL group at Visit 2. Although this adjustment improved tolerability and enabled continued participation, it may have reduced optode–scalp coupling and affected data quality (see *Diffuse Optical Tomography (DOT) data quality* section).

Diffuse optical tomography (DOT) data quality

Analyses were restricted to participants who wore the DOT cap for at least part of the session. Group-level data-quality figures are summarised in Table 2.

Table 2 DOT signal quality and motion robustness by group and visit.

Measure	Neurotypical (<i>N</i> =23)		ADHD/EL (<i>N</i> =15)		Autism/EL (<i>N</i> =16)		Overall sample (<i>N</i> =54)	
	Visit 1	Visit 2	Visit 1	Visit 2	Visit 1	Visit 2	Visit 1	Visit 2
Good quality channels	470.29 (46%)	463.05 (45%)	423.00 (41%)	427.42 (41%)	373.33 (36%)	236.67 (23%)	440.38 (43%)	414.78 (40%)
Good quality recording	65%	64%	69%	71%	58%	67%	65%	66%

Signal quality and robustness to motion artefacts were quantified as the number of good channels, as determined by the NeuroDOT²⁶ data quality function (‘FindGoodMeas’; see Methods for further details), and as the proportion of time points within these good-quality with source-detection distance < 3 cm that passed the global variance of the temporal derivative (GVTD < 0.001) threshold relative to the total recording duration (Good quality channels in Table 2). On average, 440.38 channels (43%) at Visit 1 and 414.78 channels (40%) at Visit 2 met the GVTD threshold (i.e. good quality channels). At the group level, neurotypical participants showed stable and comparatively high channels retention across the two visits (Visit 1: 46%, 470.29/1030; Visit 2: 45%, 463.05/1030), as did children in the ADHD group (Visit 1: 41%, 423.00/1030; Visit 2: 41%, 427.42/1030). Autistic participants showed lower signal quality rates overall, with an average of 36% in Visit 1 (373.33/1030), declining to 23% in Visit 2 (236.67/1030). Robustness to motion artefacts (i.e. good quality recording in Table 2) ranged from 58% to 65% across diagnostic groups at Visit 1 and from 64% to 71% at Visit 2, indicating that the majority of recording time was free from substantial motion-related signal contamination across all groups. The improvement from Visit 1 to Visit 2 is consistent with children becoming more familiar with the setup across sessions. It should be noted that the LUMO DOT system is designed with deliberate spatial oversampling, such that usable neuroimaging data can be obtained from a subset of channels even when overall yield is reduced. A channel yield of 40–43% is therefore consistent with expectations for this system and sufficient to support meaningful analyses of task-related haemodynamic responses^{23,25}.

Data quality was also influenced by hair colour and length, ranging from an average of 46% to 66% good-quality signal across visits in children with light, short hair, compared to 20% to 45% in children with dark, long hair during Visit 1. This effect was particularly pronounced in posterior regions, where hair density is higher than in prefrontal areas. Neither hair colour (blonde, i.e. very light hair colour; dark, i.e. black or dark brown hair colour; brunette, i.e. intermediate shades between blonde and dark) nor hair length (short, i.e. very short hair, approximately 1–2 cm in length; medium, i.e. hair not extending below the ears; and long, hair extending below the ears) differed significantly between groups (hair colour: $\chi^2(4, N=54)=2.68, p = 0.612$; hair length: $\chi^2(4, N=54)=4.63, p = 0.327$).

Another factor affecting data quality was the use of a chinstrap and elastic headband, applied on top of the DOT cap to exert light pressure on the tiles and improve scalp coupling.

Signal quality averaged 42% in Visit 1 and 39% in Visit 2 when both the chinstrap and headband were used. It ranged from 28% to 41% across visits when only the chinstrap was used, and from 2% to 16% when only the headband was used (typically for children who were hypersensitive and could not tolerate the chinstrap). When neither the chinstrap nor the headband was used, average signal quality was 3%.

Parental insights: likert-scale questions

Table 3; Fig. 2 present mean parental ratings across six Likert items (enjoyment of the testing session, annoyance from the DOT cap, annoyance from the VR environment, annoyance from the shutter glasses, overwhelmed by the VR immersiveness, benefit of repeated visits) rated on a scale of 1 to 5 at three timepoints (prior to Visit 1: Pre-V1, after Visit 1: Post-V1, and after Visit 2: Post-V2). For annoyance and overwhelm items, lower scores indicate less concern; for enjoyment and familiarity items, higher scores indicate more positive expectations or experiences. Table 4 summarises all within-group and between-group statistical comparisons. The non-parametric

Table 3 Parental ratings of expected and experienced aspects of the VR-DOT testing setup across diagnostic groups and timepoints. Mean ratings and SD are presented for each questionnaire item at three timepoints: prior to Visit 1 (Pre-V1), after Visit 1 (Post-V1), and after Visit 2 (Post-V2). All items were rated on a five-point Likert scale (1–5). For annoyance and overwhelm items, lower scores indicate less concern; for enjoyment and familiarity items, higher scores indicate more positive responses. * = this last question was optional and was answered after the second visit only by 20 parents in total (9 neurotypical, 2 ADHD/EL, 9 Autism/EL).

Questionnaire item	Group	Pre-V1 M (SD)	Post-V1 M (SD)	Post-V2 M (SD)
Enjoyment of the testing session	Neurotypical	4.39 (0.65)	4.06 (0.72)	4.33 (0.81)
	ADHD/EL	4.43 (0.64)	4.30 (0.94)	4.20 (0.83)
	Autism/EL	4.13 (0.91)	3.86 (1.35)	4.33 (0.71)
	Total	4.33 (0.73)	4.05 (1.01)	4.30 (0.73)
Annoyance from the DOT cap	Neurotypical	2.26 (1.13)	1.61 (0.84)	1.00 (0)
	ADHD/EL	3.07 (0.82)	1.80 (1.31)	1.40 (0.54)
	Autism/EL	3.40 (0.73)	3.29 (1.59)	3.22 (1.20)
	Total	2.81 (1.06)	2.21 (1.44)	2.10 (1.33)
Annoyance from the VR environment	Neurotypical	1.39 (0.94)	1.11 (0.32)	1.00 (0)
	ADHD/EL	1.57 (0.93)	1.20 (0.63)	1.00 (0)
	Autism/EL	2.27 (1.01)	1.93 (1.60)	1.22 (0.44)
	Total	1.69 (1.03)	1.40 (1.03)	1.10 (0.30)
Annoyance from the shutter glasses	Neurotypical	2.04 (1.02)	1.39 (0.60)	1.00 (0)
	ADHD/EL	2.36 (0.92)	1.80 (1.13)	2.20 (1.30)
	Autism/EL	3.20 (1.01)	3.29 (1.43)	3.00 (1.5)
	Total	2.46 (1.09)	2.12 (1.34)	2.20 (1.43)
Overwhelmed by the VR immersiveness	Neurotypical	1.87 (0.75)	1.22 (0.54)	1.00 (0)
	ADHD/EL	2.07 (0.73)	1.80 (1.31)	1.00 (0)
	Autism/EL	2.27 (1.16)	2.29 (1.26)	2.11 (0.92)
	Total	2.04 (0.88)	1.71 (1.11)	1.50 (0.82)
Benefit of repeated visits	Neurotypical	4.04 (0.97)	3.94 (0.93)	3.83 (1.47)
	ADHD/EL	3.71 (1.13)	4.00 (1.49)	4.40 (0.89)
	Autism/EL	4.40 (1.21)	4.64 (0.75)	4.78 (0.44)
	Total	4.06 (1.07)	4.19 (1.06)	4.40 (0.99)
Willingness to attend future studies*	Neurotypical			4.89 (0.33)
	ADHD/EL			5 (0)
	Autism/EL			4.89 (0.33)
	Total			4.90 (0.31)

Friedman test was used to assess whether ratings changed significantly across the three timepoints within each group (for Pre-V1 vs. Post-V1 in the ADHD group the Wilcoxon signed-rank test was used, as there were only $N=2$ for Post-V2). The non-parametric Kruskal-Wallis test was used to assess whether ratings differed significantly across the three diagnostic groups at each timepoint (at Post-V2, Mann-Whitney U test was used to compare the neurotypical with the autistic children due to insufficient data from the ADHD group).

Across all groups, parents anticipated that visits would be enjoyable before the first testing session and this expectation was borne out in experience, with mean enjoyment ratings remaining consistently high across all three timepoints, and no significant within- or between-group differences at any timepoint. Moreover, parental anticipation carried genuine predictive information about subsequent participation: across the full sample, parent-reported anticipated session enjoyment (rated before Visit 1) was significantly and positively correlated with children's objective engagement during Visit 1 (Spearman's $\rho=0.31$, $p=0.024$, $N=54$). Among the 20 participants who completed the post-Visit 2 questionnaire, 18 of 20 parents selected the maximum score of 5 for willingness to participate in future studies, with this near-ceiling endorsement consistent across all three groups. While this suggests high overall satisfaction among those who responded, we note that this item was completed by only a subset of families, and it should therefore be interpreted with caution rather than as representative of the full sample.

Within-group change across visits was significant for the neurotypical group for DOT cap annoyance ($\chi^2(2)=11.47$, $p=0.003$) and overwhelm by VR immersiveness ($\chi^2(2)=10.00$, $p=0.007$), indicating that both concerns resolved meaningfully over the two visits. For VR annoyance in the neurotypical group, the Friedman test could not be computed as all nine participants rated this item at the minimum score of 1 across all three timepoints, itself indicative of a complete absence of concern about the VR environment in this group. Overall cap

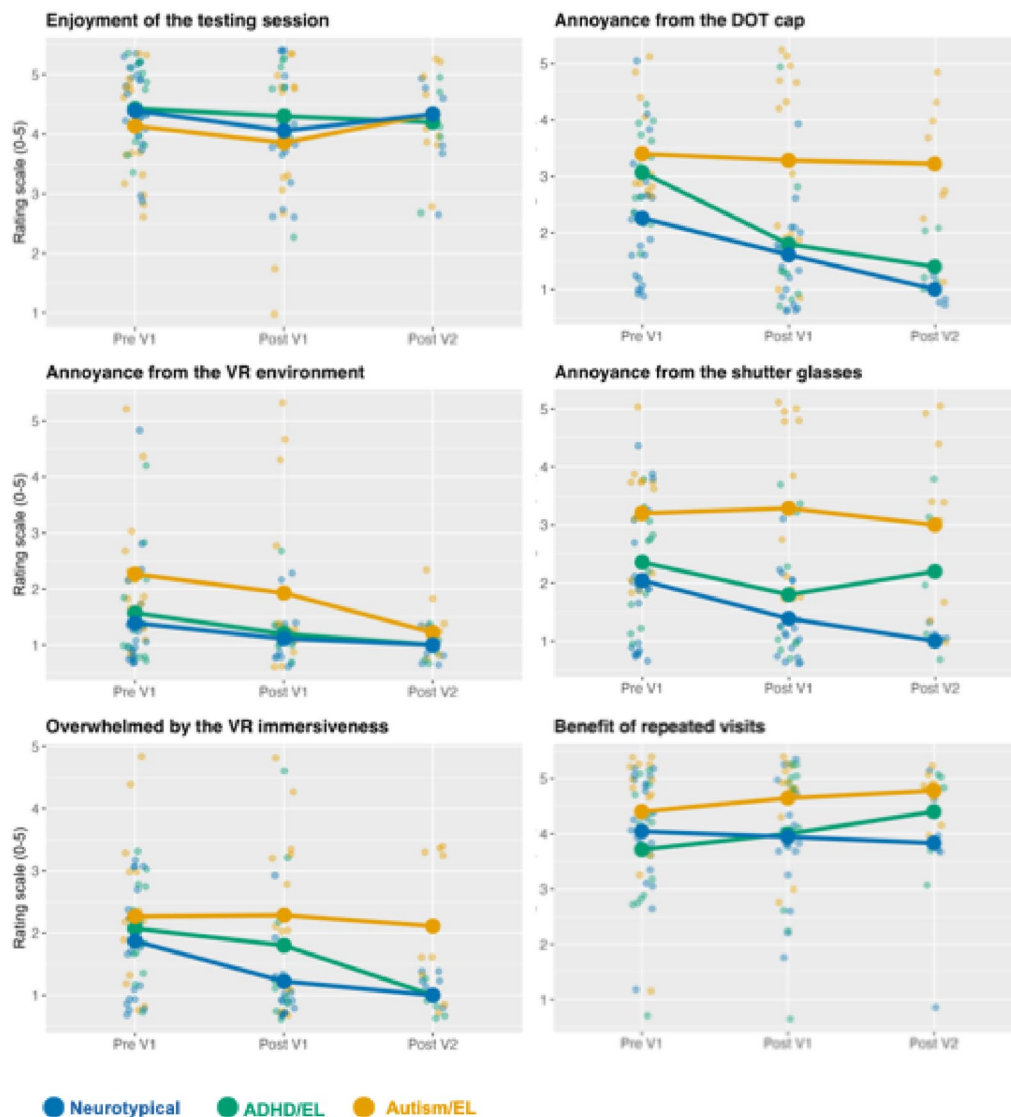


Fig. 2 Parental ratings of expected and experienced aspects of the VR-DOT testing setup across groups and timepoints (Pre-V1, Post-V1, Post V2). Blue represents neurotypical children, green ADHD/EL children, orange Autism/EL children. Lines represent group means, shaded points individual ratings.

annoyance also decreased significantly across timepoints when all groups were combined ($\chi^2(2)=7.14, p=0.028$), as did overall VR annoyance ($\chi^2(2)=6.08, p=0.048$). No significant within-group changes were observed for any item in the autistic group, confirming that ratings remained stable across all three timepoints, including for DOT cap annoyance and shutter glasses annoyance, which stayed persistently elevated. Within the ADHD group, no Wilcoxon test reached significance, though DOT cap annoyance showed a descriptive decrease from Pre-V1 to Post-V1.

Between-group differences at Pre-V1 were significant for DOT cap annoyance ($H(2)=7.56, p=0.023$), VR annoyance ($H(2)=13.28, p=0.001$), shutter glasses annoyance ($H(2)=9.72, p=0.008$), and perceived benefit of repeated visits ($H(2)=6.10, p=0.047$), with the autistic group reporting the highest anticipated equipment concerns and the highest perceived benefit of the repeated-visit design at baseline. At Post-V1, group differences persisted and, in some cases, strengthened for DOT cap annoyance ($H(2)=10.62, p=0.005$), shutter glasses annoyance ($H(2)=16.94, p<0.001$), and overwhelm by VR immersiveness ($H(2)=10.67, p=0.005$), with neurotypical

Table 4 Summary of within-group and between-group statistical comparisons for parental questionnaire Likert items. Shaded cells indicate statistically significant results, * indicates $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. # For VR annoyance in the neurotypical group, the Friedman test could not be computed as all participants rated this item at the minimum score of 1 across all three timepoints.

Questionnaire item	Within-group change across visits			Between-group differences		
	Neurotypical	ADHD/EL (V0 vs. V1)	Autism/EL	Pre-V1	Post-V1	Post-V2 (Neurotypical vs. Autism/EL)
Enjoyment of the testing sessions	$\chi^2=0.50$ $p=0.779$	W=4.0 $p=1.000$ $r=0.00$	$\chi^2=1.50$ $p=0.472$	H=1.15 $p=0.562$	H=0.21 $p=0.902$	U=44.5 $p=0.733$ $r=0.08$
Annoyance from the DOT cap	$\chi^2=11.47$ $p=0.003^{**}$	W=3.0 $p=0.094$ $r=0.63$	$\chi^2=0.96$ $p=0.618$	H=7.56 $p=0.023$	H=10.62 $p=0.005^{**}$	U=6.5 $p=0.002^{**}$ $r=0.74$
Annoyance from the VR environment	#	W=0.0 $p=0.250$ $r=0.44$	$\chi^2=4.45$ $p=0.108$	H=13.28 $p=0.001^{**}$	H=2.89 $p=0.236$	U=31.5 $p=0.169$ $r=0.33$
Annoyance from the shutter glasses	$\chi^2=2.55$ $p=0.280$	W=8.0 $p=0.406$ $r=0.31$	$\chi^2=0.25$ $p=0.882$	H=9.72 $p=0.008^{**}$	H=16.94 $p<0.001^{***}$	U=18.0 $p=0.037^*$ $r=0.49$
Overwhelmed by VR immersiveness	$\chi^2=10.00$ $p=0.007^{**}$	W=4.0 $p=1.000$ $r=0.00$	$\chi^2=0.74$ $p=0.692$	H=3.37 $p=0.185$	H=10.67 $p=0.005^{**}$	U=13.5 $p=0.005^{**}$ $r=0.66$
Benefit of repeated visits	$\chi^2=1.50$ $p=0.472$	W=6.0 $p=0.813$ $r=0.09$	$\chi^2=2.00$ $p=0.368$	H=6.10 $p=0.047^*$	H=4.92 $p=0.086$	U=30.5 $p=0.311$ $r=0.24$

and ADHD parents rating all three items at or near the minimum while autistic parents' ratings remained substantially higher. At Post-V2, direct comparison between neurotypical and autistic groups confirmed that significant differences persisted for DOT cap annoyance ($U=6.5$, $p=0.002$, $r=0.74$), shutter glasses annoyance ($U=18.0$, $p=0.037$, $r=0.49$), and overwhelm by immersiveness ($U=13.5$, $p=0.005$, $r=0.66$), with large to medium-large effect sizes in all three cases. No significant between-group differences were found for enjoyment, VR annoyance, or perceived benefit of repeated visits at any timepoint.

Parental insights: open-ended questions

Open-ended responses were analysed using directed content analysis, with responses coded against a set of themes derived from the question topics³⁸.

Question 1: Signs of distress (Table 5). Prior to Visit 1, 47 provided responses describing anticipated signs of distress in their child. The most frequently reported indicators of distress were verbal expression, withdrawal or freezing, and crying or screaming. There were group differences in the nature of reported signs: physical agitation (i.e. running, hitting, throwing, and meltdowns) was reported almost exclusively by parents of autistic children, as was stimming behaviour (i.e. such as scratching, chewing, and rocking). By contrast, withdrawal and social retreat was the most common sign of distress reported by neurotypical parents. This suggests that distress presentation differs qualitatively across groups. Examples of comments were: “red cheeks, shouting, running around wildly” (Autistic/EL parent); “He will lose interest” (neurotypical parent); “will cry, scream, run or hit” (ADHD/EL parent).

Following Visit 1, 12 parents reported observed signs of distress during the first testing session. The lower rate of reported distress relative to Visit 1 anticipations is broadly consistent with the engagement data, with neurotypical and children with ADHD showing fewer distress indicators than anticipated. Distress in the autistic group centred on equipment-related discomfort, particularly wearing multiple items simultaneously, consistent with the cap and glasses annoyance ratings reported in the Likert data. Examples of comments were: “wearing all of

Table 5 Frequency of distress sign themes by group and timepoints. Frequencies represent number of parents whose response contained content relevant to each theme. Values represent the number of parents whose response contained content relevant to each theme, with the percentage of respondents shown in parentheses.

Theme	Pre-V1			Post-V1			Post-V2					
	NT (N=26)	ADHD/EL (N=8)	ASD/EL (N=13)	Total (N=47)	NT (N=3)	ADHD/EL (N=2)	ASD/EL (N=7)	Total (N=12)	NT (N=1)	ADHD/EL (N=0)	ASD/EL (N=6)	Total (N=7)
Verbal expression	11 (42%)	3 (38%)	4 (31%)	18 (38%)	2 (67%)	1 (50%)	1 (14%)	4 (33%)	1 (100%)	–	1 (17%)	2 (29%)
	12 (46%)	2 (25%)	1 (8%)	15 (32%)	1 (33%)	–	1 (14%)	2 (17%)	–	–	–	–
Crying/screaming	8 (31%)	3 (38%)	3 (23%)	14 (30%)	–	–	1 (14%)	1 (8%)	–	–	–	–
Physical agitation	–	2 (25%)	6 (46%)	8 (17%)	–	1 (50%)	1 (14%)	2 (17%)	–	–	4 (67%)	4 (57%)
Stimming	–	2 (25%)	2 (15%)	4 (9%)	–	–	1 (14%)	1 (8%)	–	–	–	–
Physical distress signs	–	1 (13%)	3 (23%)	4 (9%)	–	–	–	–	–	–	–	–
Refusal	1 (4%)	–	1 (8%)	2 (4%)	–	–	2 (14%)	2 (17%)	–	–	2 (33%)	2 (29%)

them together distress my daughter” (Autistic/EL parent); *“she did go wide eyed and quiet when getting into the equipment”* (ADHD/EL parent).

Following Visit 2, 7 parents reported signs of distress during the second testing session. Responses were predominantly from parents of autistic children, reflecting the pattern of persistent engagement challenges in this group documented throughout the study. Reported distress centred on overstimulation and equipment sensitivity. Examples of comments were: *“over stimulation, bashing up against the walls”* (Autistic/EL parent); *“No she just didn’t like the cap and has a short attention span so snappy processes would work better”* (Autistic/EL parent).

Question 2: Calming strategies and suggested changes and improvements (Table 6). Prior to Visit 1, 38 parents suggested calming strategies for their child. Physical comfort (i.e. hugs, physical contact, and being held) was the most frequently reported strategy overall, followed by favourite toys or objects and screens or videos. Importantly, the preferred strategies differed by group: parents of autistic children more frequently reported specific objects and toys as calming, while neurotypical parents more frequently reported physical comfort. Space and quiet was reported exclusively by autistic/EL and ADHD/EL parents. Examples of comments were: *“pop it type fidgets, soft deep pile textures, quiet space, iPad with noise cancelling headphones, ‘big dog’ (her teddy)”* (ADHD/EL parent); *“he loves king of dams on YouTube and fidget toys”* (Autistic/EL parent); *“counting tends to calm him, taking him somewhere quiet and calm, a hug with his mum!”* (ADHD/EL parent).

Following Visit 1, 22 parents provided suggestions for changes to Visit 2. Suggestions differed strikingly by group. Environmental adjustments, such as dimming lights or entering the CAVE without glasses, were the most common suggestion across groups. Neurotypical parents also frequently suggested pacing and break adjustments, whereas autistic parents more often proposed equipment simplification, positive reinforcement, sensory accommodations, and modified communication approaches. Examples of comments were: *“lights off, wearing one item each”* (Autistic/EL parent); *“less communication and explanation; once we start to put on equipment, do all together at once; less toys”* (Autistic/EL parent); *“I plan to bring a reward to help my child feel it’s worth putting on the helmet”* (Autistic/EL parent).

Following Visit 2, 11 shared what has been improved compared to Visit 1. Child enjoyment and engagement was the most frequently reported theme, and staff adaptation and better preparation for individual needs was noted by both neurotypical and autistic parents. Notably, several autistic parents highlighted specific adaptive strategies that had been implemented, including involving the child in running the experiment and taking individual needs into consideration. Examples of comments were: *“you got him involved in helping run the experiment”* (Autistic/EL parent); *“on the second time the researcher was more prepared for his needs”* (Autistic/EL parent); *“trying to work out with her and taking into consideration her needs”* (Autistic/EL parent).

Question 3: Additional information and preferences (Table 7). Prior to Visit 1, 21 participants provided additional insights into aspects that could support the success of the testing sessions. The most common theme was parental presence and support, with parents of both autistic children and neurotypical children noting that their child may need them nearby or would benefit from reassurance, encouragement, and a familiar approach during the session. The need for time and choice, allowing children to proceed at their own pace, was the second most common theme, reported across all three groups. Group-specific needs were highlighted by parents of autistic children, including hypersensitivity to touch, specific communication strategies such as offering choices for children with avoidance profiles, and individual special interests that could be used to motivate engagement. Examples of comments were: *“He has Pathological Demand Avoidance (PDA) so if there is any resistance give him options i.e. would you like to put on the glasses or hat first”* (Autistic/EL parent); *“After explaining the instruction, please ask him to repeat the instruction back to you. He sometimes can drift off and misses the instruction”* (ADHD/EL parent); *“he doesn’t like when people touch him. So I think it is better first to do anything on me and after try on him”* (Autistic/EL parent).

Following Visit 1, 13 parents provided additional insights into aspects that could support the success of the testing sessions. Sensory needs were the most frequently mentioned theme, and were mentioned more often following Visit 1 than before, particularly by autistic and ADHD parents, likely reflecting direct observation of their child’s sensory responses during the session. Parental presence and support remained a commonly noted theme,

Table 6 Frequency of calming strategy themes, suggested changes, and improvement themes by group. Frequencies represent number of parents whose response contained content relevant to each theme, with the percentage of respondents within each group shown in parentheses.

Theme	Pre-V1: Calming strategies				Post-V1: Suggested changes for V2				Post-V2: improved aspects			
	NT (N=19)	ADHD/EL (N=5)	ASD/EL (N=14)	Total (N=38)	NT (N=11)	ADHD/EL (N=2)	ASD/EL (N=9)	Total (N=22)	NT (N=6)	ADHD/EL (N=1)	ASD/EL (N=4)	Total (N=11)
Physical comfort	9 (47%)	3 (60%)	4 (28%)	16 (42%)	—	—	—	—	—	—	—	—
Favourite toy/object	6 (31%)	2 (40%)	9 (64%)	14 (36%)	—	—	—	—	—	—	—	—
Screen/video	6 (31%)	1 (20%)	6 (42%)	12 (31%)	—	—	—	—	—	—	—	—
Parental presence and support	5 (26%)	2 (40%)	1 (7%)	6 (15%)	—	—	—	—	—	—	—	—
Music/songs	1 (5%)	1 (20%)	2 (14%)	4 (10%)	—	—	—	—	—	—	—	—
Space/quiet	—	3 (60%)	1 (7%)	3 (7%)	—	—	—	—	—	—	—	—
Praise/reward	1 (5%)	—	2 (14%)	3 (7%)	—	—	2 (22%)	2 (22%)	—	—	—	—
Pacing/breaks	—	—	—	—	3 (27%)	—	—	3 (14%)	—	—	—	—
Sensory accommodation	—	—	—	—	1 (9%)	2 (100%)	1 (11%)	4 (18%)	—	—	—	—
Environmental adjustment	—	—	—	—	5 (45%)	—	5 (56%)	10 (45%)	—	—	—	—
Communication style	—	—	—	—	2 (18%)	1 (50%)	2 (22%)	5 (23%)	—	—	—	—
Equipment simplification	—	—	—	—	1 (9%)	—	3 (33%)	4 (18%)	—	—	—	—
Child enjoyed/engaged	—	—	—	—	—	—	—	—	3 (50%)	1 (100%)	1 (25%)	5 (45%)
Staff adaptation	—	—	—	—	—	—	—	—	2 (33%)	—	1 (25%)	3 (27%)
No issues/same as V1	—	—	—	—	—	—	—	—	1 (16%)	—	1 (25%)	2 (18%)
Better preparation	—	—	—	—	—	—	—	—	—	—	1 (25%)	1 (9%)

Table 7 Frequency of suggested change themes by group and visit. Frequencies represent number of parents whose response contained content relevant to each theme. Values represent the number of parents whose response contained content relevant to each theme, with the percentage of respondents shown in parentheses.

Theme	Pre-V1 (anticipated needs)				Post-V1 (observed needs)			
	NT (N=10)	ADHD/EL (N=3)	Autism/EL (N=8)	Total (N=21)	NT (N=4)	ADHD/EL (N=3)	Autism/EL (N=6)	Total (N=13)
Parental presence and support	7 (70%)	1 (33%)	5 (62%)	13 (62%)	–	1 (33%)	2 (33%)	3 (23%)
Give time/choice	4 (40%)	2 (67%)	3 (38%)	9 (43%)	1 (25%)		2 (33%)	3 (23%)
Specific interests	1 (10%)	–	3 (38%)	4 (19%)	2 (50%)	1 (33%)	1 (17%)	4 (31%)
Communication needs	2 (20%)	2 (67%)	–	4 (19%)	–	1 (33%)	1 (17%)	2 (15%)
Sensory needs	–	1 (33%)	2 (25%)	3 (14%)	1 (25%)	2 (67%)	2 (33%)	5 (38%)

alongside suggestions relating to the child’s specific interests. Several parents also noted the value of minimal verbal input from experimenters, particularly for children who can become overwhelmed by multiple adults attempting to reassure them simultaneously. Examples of comments were: “*it’s best to operate with minimal verbal inputs, she can easily feel overwhelmed by too many adults trying to reassure her*” (ADHD/EL parent); “*he is a sensory seeker, anything he can touch, feel and hear really helps*” (Autistic/EL parent).

Personalisation of the testing set-up

Drawing on parental feedback from the questionnaires and observations across visits, a range of practical adaptations were implemented across the two sessions, which are summarised below.

During the session Allowing children to explore the environment freely and having sensory toys available upon arrival helped reduce initial distress and supported a smoother transition into the session. Following some of the parents’ suggestions in the pre-visit questionnaire, gentle sensory massage techniques were used during the session, particularly for sensory-seeking children. Adjusting the environment to each child’s preferences was equally important: playing a favourite cartoon during equipment setup, or offering it as a reward at the end, increased motivation and created a more positive overall experience. Storytelling, actively involving children in monitoring data quality (e.g., asking them to inform the experimenter if they noticed any red dots on the computer screen during capping, a classic sign of oversaturation), and maintaining interactive conversation were particularly effective for hyperactive children, helping to sustain attention and reduce resistance during cap placement. The ‘Sticker Trail’, in which children received a sticker after completing each step of the set-up, such as wearing the cap or the shutter glasses, provided clear structure, guided them through the process, and gave them a sense of accomplishment. Additional breaks were provided when needed, and tasks were only initiated or concluded when the child felt ready.

Between visits If a child appeared overwhelmed by specific equipment components during Visit 1, as noted by parents or experimenters, targeted adjustments were made for Visit 2. Where possible, components identified as distressing, such as the chinstrap, were removed. Less intrusive versions of equipment were also implemented: for example, with some children a band was used instead of the full motion-tracking glove, and the chinstrap was omitted during capping. These adaptations reduced overall sensory contact for more sensitive children.

Discussion

Developmental neuroscience has long struggled to include children with neurodivergent developmental trajectories. This study directly addresses that gap, providing novel, empirical evidence on how participation in wearable neuroimaging differs across neurodevelopmental profiles in young children, and introducing the first co-designed personalisation framework to systematically reduce those differences.

Neurotypical children and children with elevated likelihood of ADHD engaged with the DOT/VR setup at consistently high rates across both visits, with equipment tolerance and task completion broadly comparable between these groups. By contrast, engagement in the autistic group was markedly more variable, with a substantial proportion of children showing partial or no engagement with the task and key equipment components across both visits. Critically, however, even within the autistic group, half of the children completed the full task at Visit 1, and engagement was maintained or improved at Visit 2 following personalised adaptations, highlighting that high exclusion rates are not a fixed reality of testing autistic children, but a variable that can be actively improved. Parental questionnaire data provided a complementary subjective account that corroborates and enriches these objective findings, revealing that equipment-related concerns were anticipated by carers and experienced differently across groups. Interestingly, these differences persisted for the autistic group despite two exposures to the testing sessions and targeted adaptations.

Children with elevated likelihood of ADHD showed comparable engagement to neurotypical participants. Children with ADHD are often considered poor candidates for neuroimaging protocols due to elevated activity levels and attention regulation differences, and are often excluded from studies that require sustained stillness or strict behavioural compliance²⁷. The near-ceiling task completion and equipment tolerance rates observed in this work, alongside the near-significant reduction in DOT cap annoyance from pre-testing to Visit 1 in the ADHD group suggest that a VR-based paradigm, with its greater movement tolerance and immersive, game-like structure, may be particularly well-suited to this group, effectively circumventing the procedural barriers that typically drive ADHD-related exclusion in conventional laboratory settings. However, we acknowledge that among the 15 children in the ADHD group, only 2 had a clear diagnosis at the time of testing. Given that the recurrence of elevated likelihood of ADHD in first-degree relatives is estimated at approximately 10–20%¹, this group should be considered as only modestly enriched for ADHD polygenic liability rather than as representative of children with a clinical diagnosis. Therefore, these results need to be replicated in a larger sample of children with ADHD.

The autistic group's engagement profile was considerably more variable. While task performance itself did not differ significantly across groups, suggesting the cognitive demands of the Go/No-Go task were broadly accessible to all children, engagement with the equipment differed markedly. Among the pieces of the equipment involved in this study, the shutter glasses were the greatest barrier, with fewer than half of autistic children wearing them for the full testing session at Visit 1, compared to the other pieces of equipment. However, parental questionnaire data suggest that subjective experience of the cap was more challenging than its objective tolerance rates alone might imply. In fact, DOT cap annoyance ratings in the autistic group remained persistently elevated across all three timepoints, comparable to shutter glasses annoyance, while VR annoyance decreased substantially from pre-testing to Visit 2. This divergence between objective tolerance and subjective discomfort may suggest that some autistic children wore the DOT cap for the full session despite experiencing discomfort with it. The open-ended responses added important qualitative depth: parents of autistic children described a qualitatively different distress profile compared to neurotypical and ADHD parents, characterised by physical agitation, stimming, and meltdown-type responses rather than the withdrawal and verbal expression more commonly reported for neurotypical children. This seems to suggest that distress in autistic children during neuroimaging protocols may not only be more frequent but also more intense and more visible, a factor with direct implications for experimenter training and protocol design. Despite these challenges, the between-visit trajectory for the autistic group was not uniformly negative. Of the autistic children who showed no or partial engagement at Visit 1, the majority showed some level of engagement at Visit 2, with four children who had shown no engagement at Visit 1 demonstrating partial engagement at the second visit, suggesting that even a single prior exposure to the paradigm can shift the trajectory of participation. The open-ended data revealed that parents of autistic children specifically highlighted equipment adaptation and child-centred adjustments as improvements at Visit 2, including involving children in monitoring data quality and tailoring the session to individual needs. This pattern is consistent with the literature on repeated exposure and graduated familiarisation in autistic children²⁸, and suggests that multiple visits to the lab may be crucial for the successful assessment of these children in a laboratory setting. Familiarisation with the equipment could also begin before arrival: as demonstrated in paediatric MRI research using mock scanners^{29,30},

providing families with a neuroimaging cap or a simplified mock system to explore at home ahead of testing could allow gradual, low-pressure desensitisation to the equipment, potentially reducing the participant's stress and improving the success of the first testing session.

These findings should nonetheless be interpreted in light of an important limitation concerning the characterisation of our sample. We did not conduct formal assessments of intellectual functioning, and therefore do not have systematic data on the presence of co-occurring intellectual disability among participants. More broadly, standardised measures of cognitive level and of autistic or ADHD symptom severity were not available, as diagnoses and assessments were carried out externally by qualified health services rather than by the research team. Although no children were excluded on this basis, participation was voluntary and required families to attend the laboratory twice. This may have introduced a degree of self-selection, whereby autistic children with more significant support needs, including those with intellectual disability, may have been less likely to take part. Our sample may therefore under-represent the full spectrum of the autistic population, and because we lack detailed cognitive, symptom, and demographic data, and the participation patterns reported here should be interpreted accordingly. Future studies would benefit from systematically documenting intellectual functioning, adaptive ability, symptom severity, and socioeconomic background, and from developing recruitment and testing approaches that actively facilitate the inclusion of children with higher support needs, who arguably stand to benefit most from more accessible neuroimaging methods.

The DOT signal quality findings extended and nuanced the engagement data. Overall, channel quality yielded rates of 43% at Visit 1 and 40% at Visit 2, which fall within the range reported for wearable fNIRS and DOT systems in paediatric populations²⁵, though the autistic group's declined from 36% to 23% between visits likely reflects the compounding effects of reduced cap tolerance and chinstrap removal for some children in this group. This trade-off between participant comfort and signal integrity is an inherent challenge when conducting neuroimaging with hypersensitive populations, and underscores the importance of the iterative, co-designed approach described in this paper. Here, by quantifying the signal quality cost of chinstrap removal, we provided the evidence base needed to motivate engineering investment in more tolerable fastening solutions. Chinstrap design should therefore be treated as a priority target for future iterations of wearable DOT systems intended for neurodivergent paediatric populations. In collaboration with Gowerlabs Ltd, two potential hardware modifications were explored in response to these findings: spring-loaded optode tiles, which would reduce the need for external pressure from a chinstrap by improving passive scalp contact, and a band-based system as an alternative to the full cap. Neither modifications could be tested in time for the current study, but both represent promising directions for DOT hardware design and illustrate the value of embedding researcher–industry dialogue within the data collection process. Beyond equipment tolerance, hair characteristics, particularly dark, thick, and long hair, exerted a substantial influence on DOT signal quality³¹, in some cases exceeding the effect of diagnostic group. This is an inherent limitation of optical neuroimaging technologies, which carries important implications for equity and representativeness. Parting the hair beneath each optode during cap placement, using optodes with hair-parting tips or light-guiding fibres, and braiding or sectioning longer hair prior to the session are some of the practical strategies can help mitigate these effects and increase the optodes coupling with the scalp. From a hardware perspective, ongoing development of high-density optode arrays and improved light delivery systems may reduce the impact of hair over time. We recommend that future studies systematically record and report hair characteristics, both to enable appropriate interpretation of signal quality and to support the development of more inclusive optical neuroimaging technologies.

The parental questionnaire data highlighted the importance of engaging with parents for pre- and post-visit consultation as a standard component of developmental neuroimaging protocols, especially when working with different neurodevelopmental profiles. Group differences in anticipated and experienced equipment concerns, already present at pre-testing and persisting through both visits for the autistic group, together with the finding that anticipated enjoyment significantly predicted subsequent engagement across the sample, showed that parental knowledge of their child's sensory profile is a reliable and informative predictor of participation challenges. Incorporating structured pre-visit parental consultation into neuroimaging protocols therefore serves both an

ethical function, ensuring families feel heard and respected, and a practical one, enabling researchers to anticipate and mitigate participation barriers before they arise.

Additionally, the qualitative data from the open-ended questions revealed a degree of individual specificity in children's needs that cannot be captured by group-level statistics alone. Parents described highly individualised calming strategies, from specific videos and fidget toys to sensory massage and breathing exercises, as well as communication preferences, hypersensitivity and motivational approaches that proved essential for sustaining engagement. These findings underscored that inclusive neuroimaging research is not achieved through standardised accommodations applied uniformly to a diagnostic group, but through genuine responsiveness to the individual child. An important question this raises is how individualised accommodations can be reconciled with the experimental standardisation required for valid neuroimaging inference. We would argue that these goals are not fundamentally in conflict, provided a clear distinction is maintained between adaptations to the context of testing (such as the environment, the equipment setup, the interpersonal interactions, and the pacing) and the experimental task itself, which should remain standardised across participants.

Despite these challenges, all parents who completed the questionnaire across the three groups expressed willingness to participate in future studies, suggesting that high overall satisfaction with the protocol is achievable even when individual sessions are demanding. This finding is encouraging for the field and indicates that investment in child-centred, adaptive protocol design may foster greater family engagement and improve study retention. In particular, parents of autistic children rated the perceived benefit of repeated visits highest of all three groups (consistently across visits), even if equipment-related concerns remained persistently elevated throughout the study. This suggests that autistic families recognised and valued the opportunity for iterative adaptation, even when the adaptations made across two visits were not sufficient to fully resolve their child's difficulties with the testing set-up. The pre-visit video was endorsed as useful by several autistic parents, and consistent with evidence from clinical practice on the benefits of advance preparation and environmental familiarisation for autistic children²⁸, these preparatory strategies appear to meaningfully reduce uncertainty and support smoother session transitions. Future studies should treat pre-visit familiarisation not as an optional enhancement but as a core protocol component, particularly when testing autistic or otherwise hypersensitive children.

Taken together, the present findings support a four-phase personalisation framework for inclusive developmental neuroimaging with neurodivergent children. In the pre-visit phase, structured parental consultation, covering distress indicators, calming strategies, and individual preferences, should be combined with familiarisation materials to reduce uncertainty and enable targeted preparation. In the in-session phase, experimenters should be equipped with a repertoire of child-centred engagement strategies, including storytelling, child involvement in the research process, sensory accommodations, and flexible reward systems, and should be prepared to adapt in real time based on the child's responses. If more than one visit to the lab is planned, systematic debriefing of parents and experimenters following each session should inform targeted protocol modifications for subsequent visits, with the explicit goal of reducing barriers identified in the preceding session. A fourth and equally important dimension of this framework is engagement with the neuroimaging industry. Sharing participation rates, signal quality data, and equipment-specific tolerance findings directly with hardware developers enables evidence-based refinement of device design between studies, creating a feedback loop in which real-world testing informs next-generation equipment that is more tolerable, more accessible, and better suited to neurodivergent paediatric populations. This exchange was not retrospective but embedded throughout the data collection process, with equipment tolerance and signal quality findings communicated to Gowerlabs Ltd. on an ongoing basis, a model of real-time researcher–industry collaboration that we propose, whenever possible, as a standard component of inclusive neuroimaging research partnerships. This iterative, co-designed approach represents a departure from the conventional model of standardised neuroimaging protocols and is consistent with emerging calls for participatory research designs in neurodivergent populations^{19,32,33}. Critically, this framework is not specific to the DOT and VR setup used in the present study, but it is applicable to any neuroimaging modality and any paediatric population, and provides the field with both the motivation and the evidence to move beyond one-size-fits-all

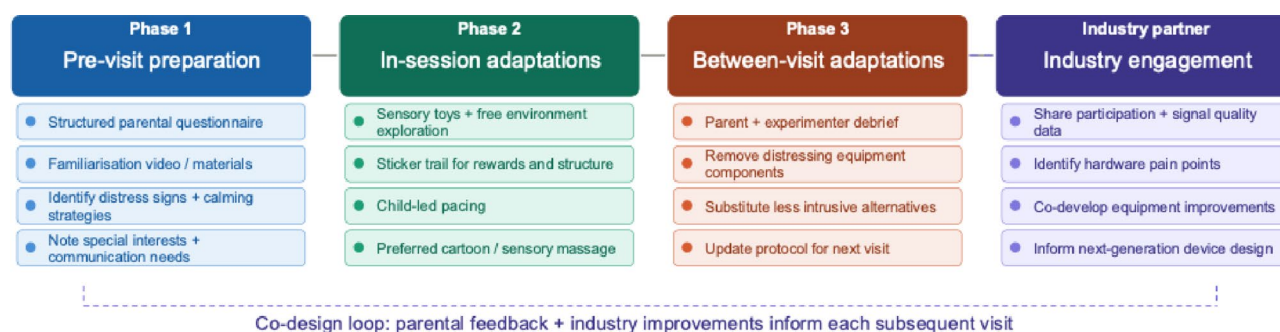


Fig. 3 Graphical representation of the guidance for the developmental neuroimaging field about improving studies inclusivity.

neuroimaging protocols. We summarise this in Fig. 3, as guidance for other researchers in the field, with the aim of providing concrete support to improve inclusivity in neuroimaging studies with developmental populations.

In conclusion, this study demonstrates that participation in wearable neuroimaging is shaped by neurodevelopmental profile in ways that are both predictable and, at least in some cases, modifiable. Neurotypical children and children with ADHD engaged readily with the combined VR and DOT paradigm, whereas autistic children experienced equipment-specific barriers that persisted across visits but were reduced through personalised, iterative adaptation. Together, these findings point to a clear path forward: embedding parental expertise, real-time flexibility, repeated familiarisation, and ongoing dialogue with industry into the research process. In its current form, this setup remains a research tool rather than a clinical instrument, but its enduring value lies in characterising the neural mechanisms that give such behavioural markers meaning, helping to validate and interpret the simpler signals that more scalable tools can capture in practice. Ultimately, making neuroimaging research accessible to neurodivergent children is not only a methodological challenge but an ethical imperative: the children most likely to benefit from early neurodevelopmental insight are precisely those most often excluded from the research designed to help them.

Methods

Participants

Fifty-four children aged 3 to 7 years took part in the study (21 girls, 33 boys; $M=62.72$ months, $SD=14.97$). Among them, twenty-three were typically developing children (8 girls, 15 boys; $M=60.00$ months, $SD=13.67$). Sixteen children were assigned to the autism group (Autism/EL, 4 girls, 12 boys; $M=66$ months, $SD=14.68$), including children with a confirmed autism diagnosis ($N=12$), one child at higher likelihood of autism due to having a first-degree relative with autism ($N=1$), and three children with autism and an elevated likelihood of ADHD based on having a first-degree relative with an ADHD diagnosis ($N=3$). Fifteen children were assigned to the ADHD group (ADHD/EL, 9 girls, 6 boys; $M=61.86$ months, $SD=17.25$). As formal diagnostic pathways for ADHD are typically completed later in childhood, confirmed diagnoses are less common in this age range^{34,35}. Therefore, this group included both children with a confirmed ADHD diagnosis ($N=2$) and children at higher likelihood of ADHD ($N=13$), due to having a first-degree relative with ADHD or ADHD and autism, or being currently under assessment for ADHD. Diagnoses were not conducted as part of this study. Children entered the Autism/EL or ADHD/EL groups on the basis of a clinical diagnosis or ongoing assessment carried out externally by qualified health services, or on the basis of a first-degree relative with a confirmed diagnosis. Where children had more than one relevant diagnosis or elevated likelihood, they were assigned to the group corresponding to their principal profile, determined in consultation with parents and informed by assessment information, to avoid arbitrary or overlapping classification. Children in the neurotypical group had no diagnosis

of a neurodevelopmental condition, were not under assessment for any such condition at the time of testing, and had no first-degree relative with a diagnosis of x or ADHD.

Children were recruited through the Centre for Brain and Cognitive Development (CBCD) database and social media, and tested in the ToddlerLab CAVE at the CBCD, Birkbeck, University of London. Children were excluded if they had a known genetic or neurological condition. Written informed consent was obtained from the toddler's caregiver prior to the start of the experiment. The study was approved by the ethical committee of the School of Psychological Science, Faculty of Science, Birkbeck, University of London (No. 2324007), and all methods were performed in accordance with the relevant guidelines and regulations.

Materials and experimental setup

The Cave Automatic Virtual Environment (CAVE)

The Cave Automatic Virtual Environment (CAVE, Fig. 4A) at Birkbeck ToddlerLab consists of four-sided, custom-designed display system (Mechdyne Corporation) equipped with four projectors: three projection walls (front and sides) and a projection floor. The frontal display measures 4.3×2 m, the two side projection walls measure 2.4×2 m each, and the projection floor measures 4.3×2 m. The front wall and floor utilise two overlapped and blended single-chip laser projectors, each with a resolution of 2716×1528 pixels, resulting in a total resolution of 3297×1528 pixels. The side walls are each powered by a single laser projector with a resolution of 2716×1528 pixels. For active stereo viewing and ensure an immersive visual experience in the CAVE, participants wear custom-built, child-sized liquid crystal display (LCD) shutter glasses. In addition, to facilitate real-time interaction with virtual objects, the CAVE system is equipped with four six-degree-of-freedom optical motion-tracking cameras (Vero 1.3 X, Vicon), positioned at the top corners of the environment. Passive markers for head tracking are affixed to the shutter glasses, enabling real-time reorientation and rotation of the virtual scene in accordance with the participant's head position. In the current study, we asked participants to wear a cycling glove fitted with passive markers to engage with virtual objects in the scene (see Dima et al., 2024; Bulgarelli, et al., 2023 for more details) (Fig. 4B).

The VR task was developed using Unity (v2019.4.18f1) in conjunction with a CAVE-specific plugin (get-Real3D, Mechdyne) to ensure synchronisation of visual stimuli across all projection surfaces. The task took place in a virtual playground environment, designed to be engaging and familiar to young children of this age.

High-density diffuse optical tomography (DOT) data acquisition and signal quality assessment

Brain activity was recorded using the LUMO system, a high-density diffuse optical tomography (HD-DOT) device developed by Gowerlabs Ltd (<https://www.gowerlabs.co.uk/>) (Fig. 4B). The system comprises 12 modular tiles, each containing four photodiodes and three dual-wavelength LEDs emitting at 735 nm and 850 nm. These modules were assembled into a tailored chain-like docking system and secured within a neoprene cap to probe activity in dorsal and prefrontal areas. The complete sensor arrangement yields a total of 1728 dual-wavelength and multidistance (1–43 mm source–detector separation channels, with data sampled at a frequency of 12 Hz. The cap size (circumference of 52–54 cm or 54–56 cm) was selected based on measurements of the participant's head circumference, nasion-to-inion distance, forehead width, and ear-to-ear distance. Photographs of the cap placement from multiple viewpoints (at least one from the front and one from the side) were taken to verify accurate placement. To achieve optimal cap placement over the frontal cortex and maintain consistency across participants, we ensured that the front edge of the cap was positioned precisely above the participant's eyebrows.

Time series were trimmed to exclude the first 10 s after acquisition onset and 30 s following the final trigger. Data quality was assessed across the 1030 channels with a source–detector separation of 1–43 mm as these channels are most likely to capture signals from the extracerebral and cerebral compartments of the head which are not too weak due to attenuation.

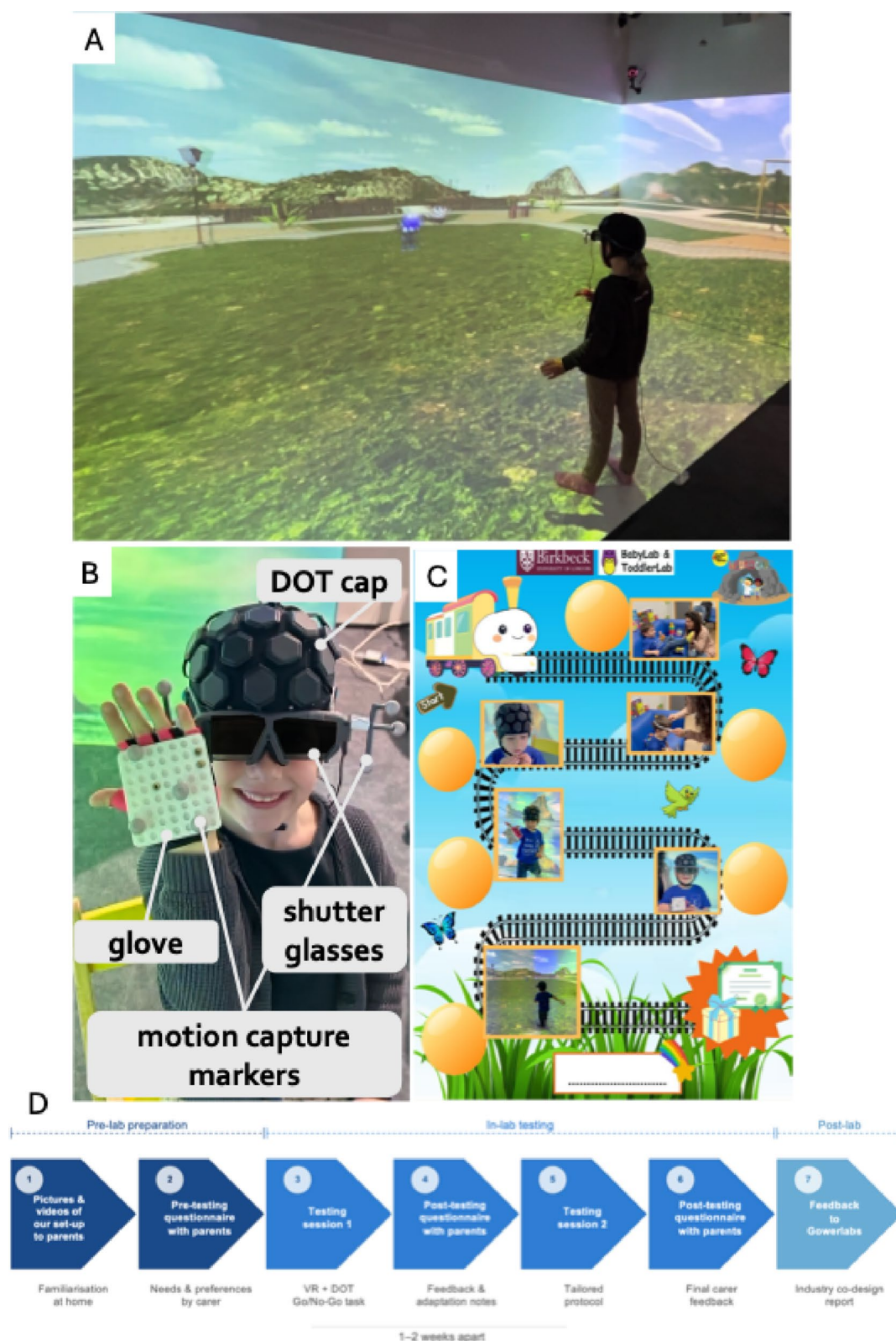


Fig. 4 Graphical representation of the main methods and materials used in this study. **(A)** A participant in the CAVE during the inhibitory control task. **(B)** Components of the equipment worn by a participant. **(C)** Study chart showing all the steps of the testing session. **(D)** Graphical representation of the study procedure. Informed consent for the publication of these photographs was obtained from the children's parents.

DOT data were preprocessed using the NeuroDOT toolbox²⁶. Data quality was assessed using NeuroDOT's FindGoodMeas function (within Plot_RawData_Cap_DQC). Good measurements were identified using a standard deviation threshold (bthresh=0.075), low light intensity threshold (FloorTh= 1×10^{-8}), excessive signal range threshold (AbsDiff=0.5), frame-to-frame change threshold based on the absolute temporal derivative (DtKeep=1). Raw intensity data were log-transformed, detrended, and temporally filtered (high-pass: 0.02 Hz; low-pass: 1 Hz). Superficial physiological signals were regressed out using short-separation channels (< 10 mm)^{36,37}. Exploiting the high density of our array, we evaluated the presence of motion artifacts based on their spatial distribution. Motion artifacts were quantified using the global variance of the temporal derivatives (GVTD), calculated on good-measurement channels with source–detector separation < 30 mm. Time points with GVTD values below 0.001 were retained. A GVTD normalized index was then calculated as the proportion of retained time points over the total recording duration, providing an index of robustness to motion artifacts, with higher values reflecting better data quality and more artifacts-free data.

Throughout the study, findings relating to equipment tolerance, signal quality, and child-specific sensory challenges were shared on an ongoing basis with our industry partner, Gowerlabs Ltd, enabling iterative dialogue about potential hardware modifications and informing the development of future iterations of the LUMO DOT system for use with neurodivergent paediatric populations.

The functional neuroimaging results, comprising task-related haemodynamic responses and test-retest reliability across the two visits, are reported in a separate forthcoming publication.

The inhibitory control task

The task was the same used previously in the CAVE with $N=30$ typically developing 3-to-7-years-olds^{22,36}. In the CAVE, participants found themselves in a virtual playground with an elephant-shaped blue bubble machine. Children were instructed to pop only the blue bubbles (Go trials) using the hand wearing the motion-tracking glove, while avoiding the red ones (No-Go trials). The task was block designed, with six go and six go/no-go mixed (50% Go trials and 50% No-Go trials) alternated blocks. Each block had 9 to 11 trials each presented for 2 s with an intertrial interval of a maximum of 1 s. Blocks were spaced by rest periods with a randomized duration between 8 and 12 s in which children were asked to fixate a star on the elephant's trunk. The whole task lasted approx. 6 min. The task stopped if the participant completed all the trials, or showed signs of distress.

Testing sessions procedure and parents' insights

Figure 4D shows a graphical representation of the testing sessions procedure, as well as families and industry partner engagement.

Participants were invited to take part in two study sessions (one to two weeks apart) in the CAVE at Birkbeck ToddlerLab in London, UK. Prior to the first visit to the lab, caregivers were asked to watch a short video explaining the study and the equipment used (<https://youtu.be/2UCWVK-iEck?si=YflaOUIEUncpL0->) with their child. Following this, they completed a questionnaire to provide information on how their child might respond to the testing setup, including six items rated on a five-point Likert scale (1 = not at all, 5 = very much): anticipated enjoyment of the visit; anticipated annoyance with the DOT cap, the VR environment, and the shutter glasses; anticipated overwhelm due to the immersiveness of the CAVE; and perceived benefit of repeated visits for familiarisation with the testing environment. Caregivers also responded to three open-ended questions at each timepoint, covering signs of distress specific to their child, objects or strategies that tend to calm their child when distressed, and any additional information or preferences that would assist in providing the best possible experience (questionnaires and open-ended questions are reported in the Supplementary Materials).

On the day of testing, children were welcomed into the ToddlerLab, and the needs identified from the pre-testing questionnaire were accommodated where possible (e.g., letting them play with their favourite toy, cartoon, or snack). Participants were given time to freely explore the CAVE before the testing session and had some time to

play with their parents and the researchers. A study chart illustrating all the necessary steps of the testing session (Fig. 4C) was developed to guide children through the study and reward their compliance with stickers. The steps included: (1) wearing non-grip socks to play in the CAVE; (2) having their head measured; (3) wearing the optical imaging cap; (4) wearing the motion-tracking glove; (5) wearing the shutter glasses; (6) playing the task in the CAVE. Upon completing each step, children received a sticker for their chart as a reward or their preferred toy or snack as encouragement. After putting on all the necessary equipment, the child was invited to practice the task until the experimenter determined they were confident with the game (see *The inhibitory control task* section).

After the first testing session, any feedback from the carer and the child regarding improvements to the child's comfort and compliance was recorded by the experimenter. Moreover, the experimenter recorded whether the child completed the task fully, partially (i.e., completed between 2 and 6 blocks), or did not complete it, and whether each component of the equipment (motion-tracking glove, DOT cap, shutter glasses) was worn for the entire duration of the testing session, worn only partially (i.e., for between 2 and 6 blocks), or not worn. To examine whether parental anticipation predicted subsequent participation, Spearman's rank correlations were computed between parent-reported anticipated session enjoyment and children's objective engagement. To characterise participant hair features that may affect DOT signal quality, testers recorded hair colour, categorised as blonde (very light hair colour), dark (black or dark brown hair colour), or brunette (intermediate shades between blonde and dark), and hair length, categorised as short (very short hair, approximately 1–2 cm in length), medium (hair not extending below the ears), or long (hair extending below the ears).

Before the second visit, parents were asked to complete the same questionnaire they had completed prior to the first lab visit (the six items rated on a five-point Likert scale and the three open-ended questions), with wording adjusted to reflect retrospective experience. We also asked additional insights about any changes they felt should be made to improve their child's compliance and overall experience, based on their first visit to the lab.

During the second visit, the child performed the same task, with tailored setup adjustments based on observations from the first session and parental feedback where possible (for example, wearing one piece of equipment at a time, allowing time between steps, or entering the CAVE with the lights off). After the second visit, parents completed the same questionnaire again, to provide their final insight of their child's comfort and compliance with the tailored testing set-up, allowing us to evaluate whether the adjustments made after the first visit improved the child's comfort.

Recording parents' insights prior to the first visit and after the two testing sessions allowed longitudinal tracking of parental expectations against actual experience across the two visits. The non-parametric Friedman test was used to assess whether parental ratings changed significantly across the three timepoints (Pre-V1, Post-V1, and Post-V2) within each group. For the ADHD group, data at all three timepoints were insufficient for a Friedman test, as only two parents completed questionnaires at Post-V2; therefore, only the change between Pre-V1 and Post-V1 was assessed using the non-parametric Wilcoxon signed-rank test. The non-parametric Kruskal-Wallis test was used to assess whether ratings differed significantly across the three diagnostic groups at each timepoint. At post-Visit 2, insufficient ADHD data precluded a three-group comparison; hence group differences between neurotypical and autistic children were assessed using the non-parametric Mann-Whitney U test. Non-parametric tests were selected throughout given the ordinal nature of Likert scale data and the small sample sizes within groups at some timepoints.

For the open-ended questions, responses were analysed using directed content analysis³⁸, a qualitative method in which data are coded against a set of predefined themes in advance based on the question content and established literature on sensory processing, distress expression, and participation of neurodivergent children in lab studies (see Tables 5, 6 and 7 for themes were identified for the three open-ended questions). Responses of 'no', 'none', or equivalent were also excluded.

At the end of each visit, all children received a thank-you gift. Where a specific interest or preferred item had been identified by parents in the pre-visit questionnaire (for example, a favourite character or toy), a corresponding item was purchased in advance and given to the child, individualising the reward to the child's preferences.

Otherwise, children received a standard thank-you package, which included a certificate of attendance, a t-shirt (“I am a young scientist”), and small lab-branded items such as a squashy brain, fidget toy, pencil, or rubber.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-026-71437-x>.

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Data availability The data that support the findings of this study cannot be publicly shared due to privacy issues, but are available from the senior author upon reasonable request.

Declarations

Competing interests This work involves the application of a technology developed by Gowerlabs Ltd, a UCL spin-out company, with which S.P. and N.E. are affiliated.

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