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Learning to work together: Designing a multi-user virtual reality game for social collaboration and perspective-taking for children with autism

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ABSTRACT

Children with Autism Spectrum Disorders (ASD) find it difficult to engage in reciprocal, shared behaviours and technology could be particularly helpful in supporting children's motivations and skills in this area. Designing educational technologies for children with ASD requires the integration of a complex range of factors including pedagogical and cognitive theories; the affordances of the technology; and the real-world contexts of use. This paper illustrates how these factors informed the design of a novel collaborative virtual reality environment (CVE) for supporting communicative perspective-taking skills for high-functioning children with ASD. Findings from a small-scale study involving eight typically developing (TD) children (aged 8 years) and six children with ASD (verbal mental age 9 years) are also reported. Children with ASD were supported to be reciprocal and collaborative in their responses, suggesting that this CVE could form the basis for a useful technology-based educational intervention.

1. Introduction

Autism Spectrum Disorder (ASD) is characterised by pervasive difficulties in social interaction and communication, and a restricted range of interests and behaviours [1]. Approximately 1 in every 100 children in the UK [2] is diagnosed with an ASD; with around 700,000 people with autism living in the UK [3]. The economic cost to society of supporting individuals with autism and their families is significant with the estimated annual cost at £3.1 billion in the UK, and $61 billion in the US [4]. Consequently, finding ways to more effectively educate and support individuals with autism to improve outcomes, and decrease reliance on specialist provision, remains a research priority for individuals and their families [5]. Recent reviews of the research evidence for technologies for autism have underscored both the interest in, and continued potential of, developing and applying technologies for addressing this need (e.g. [6–11]). Given the significant costs involved in providing specialist provision for autism, it has also been emphasised that technologies may offer a cost-effective and accessible means of assessing, and targeting, children's learning needs [12,13,8].

This paper applies a conceptual model of learner-centred design [14] to illustrate a novel collaborative virtual environment (CVE) for children with autism, designed with teacher input to support collaboration and reciprocity in behaviour and communication. A preliminary observational study is then reported that explores whether the CVE supported these behaviours between pairs of age-matched children with ASD, and pairs of typically developing children. The study suggests that children with ASD were supported by the structuring of the CVE-based tasks, and teacher facilitation, to collaborate and communicate in a reciprocal way, although they less collaborative and task-focused overall compared to the typically developing children. The following sections describe the background and rationale for the design and development of the CVE before presenting the methods and detailed results of the small-scale study.

2. Background

2.1. Designing technologies for children with autism

The number of peer-reviewed papers on technology and autism has risen substantially since 2001 [15] and evidence from a recent meta-analysis examining learning outcomes for children with autism in technology-based interventions showed positive results [13]. These reviews call for further research to explore

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the benefits of technology-based educational intervention more widely and to strengthen the evidence base. Notably, Ploog et al. [15] concluded that: "*Properly designed* CAT (computer-assisted technologies) programs may be advantageous in helping children with ASD attain skills for increased adaptive functioning. *A problem that often arises is that the majority of the available programs have not been developed specifically for this population*" (p. 319; emphasis added). This leads to the question: what does it mean for a technology to be specifically designed for children on the autism spectrum? Researchers have provided some insights although the following suggestions are by no means exhaustive or definitive.

Firstly, there seems to be agreement that educational technologies for autism should be designed for supporting learning in the core areas of difficulty characteristic of an ASD diagnosis i.e. social communication and interactions. For example, technology-based research has targeted (*inter alia*) social conversation, language, play, and adaptive behaviours [15,11]. Understanding, and focusing on, the core difficulties of autism as the basis for designing effective educational curricula is not confined to technology-based learning approaches, and is recognised as best practice in autism education generally [16–20].

Secondly, the value and importance of user-centred design has been recognised, with researchers often incorporating the views of parents, practitioners and children with autism into the development of technology-enhanced learning (TEL) environments for autism (e.g. [21–27]). The emphasis on user-involvement is not specific to autism but reflects a wider understanding about the ethical and practical advantages of gaining insights from the intended user population in technology design (e.g. [28–30]). Nevertheless, there are valuable discussions about the extent to which the methods that are used to involve users and seek their views need to be adapted to accommodate autism-specific characteristics and communication strengths/preferences. For example, when involving children with autism, researchers have successfully used more visual and structured methods and materials, and provided concrete examples to initiate and prompt ideas rather than relying on abstract concepts for discussion [31–33].

Thirdly, there is increasing awareness about the need to consider the situated context of use in which the learning is intended to take place; in other words, to move away from a "technologically determinist perspective" [34, p. 7] towards the development and implementation of technologies in the places where people are actually going to want to use them i.e. in homes and schools (e.g. [35–38]). It is important to involve members from the autism community in order to evolve a more ethical, informed and situated approach to research [5,39], and so interdisciplinary teams are essential [40,27]. Consequently, there is a need for researchers to work much more closely with schools to develop meaningful and context-appropriate ways of supporting the learning of children with ASD [41]. Therefore, while there are non-autism-specific as well as non-technology-specific principles that can be applied to designing technologies for autism, it is also crucial to be informed by a good understanding of autism in order to decide whether there are specific features that need to be considered to more effectively support children's learning (cf. [18]).

2.2. Theory, Technology and Thoughts (3T): conceptual approach to the learner-centred design of technologies for autism

Parsons and Cobb [14] argue that designing educational technologies for autism is complex territory, requiring consideration and integration of a range of factors. They propose a "triple-decker sandwich" (p. 421) model of learner-centred design for autism focusing on Theory, Technologies and Thoughts (3T), as a way of making explicit the many design decisions and influences that impact on how educational technologies are developed. The authors argue that the sandwich metaphor makes sense because only by bringing all three layers together can an effective product (sandwich) be made to support successful learning outcomes for children. The 3T model is applied below to illustrate the design decisions involved in the creation of a CVE called *Block Challenge*. This was one of the prototypes produced in the COSPATIAL project which was funded by the European Commission FP7 Programme to develop collaborative technologies to support the engagement and communication of children with autism in the classroom [23,42]. Inspiration for the 3T model came from early scoping of the field and the identification of "best practice" features of technology design for supporting the learning of children with autism [26]; the 3T model was further refined and clarified through the development of the *Block Challenge* prototype [14].

The core aspects of the 3T model described by Parsons and Cobb [14] for designing educational technologies for autism are:

1. *Theory*—the top-down disciplinary theories that are used to inform the development of educational tasks;
2. *Technologies*—the specific affordances of the technology/ies developed and applied for supporting learning and interaction; and
3. *Thoughts*—the grounded, bottom-up influences of the intended context(s) of use and the perspectives of the target users (e.g. children, parents, teachers, other professionals).

2.3. Illustrating the 3T model approach in practice

In terms of *Theory* the development of *Block Challenge* drew upon constructivist theories of learning which emphasise the importance of learners working together on tasks and being scaffolded in their learning via peers and teachers. There is good evidence from technology-based (e.g. [43]) and non-technology-based research [44–46] about the value of such pedagogical approaches for promoting good learning outcomes for children, including those with special educational needs (SEN). There is also good evidence that peer interactions can promote positive social outcomes for children with autism when paired with typically developing children [47,48] and other children with autism [49].

Additionally, theories concerning the needs of autistic learners were helpful regarding the best practice requirement for focusing on core difficulties as targets for educational intervention (noted above); in this case, the socio-cognitive difficulties experienced by children on the autism spectrum relating specifically to collaboration and reciprocity in behaviour and communication [50,51]. In this context, Bauminger [52–54] demonstrated that supporting children with autism to focus on both thinking and behaviour, and to reflect on their experiences and observations with peer or teacher facilitation (i.e. scaffolding), can effectively support social understanding. Thus, we drew across these theories to specify that the prototype design needed to (a) target core difficulties in reciprocal social communication and interaction; (b) support children's thinking and behaviour; (c) scaffold children's interactions; and (d) enable children to work on tasks with each other in an engaging way.

The affordances of the *Technology*, therefore, needed to be in alignment with this theoretically-informed approach. Given the focus on collaboration in the project, we selected technologies that could only be used by more than one person interacting with them concurrently: CVEs and Shared Active Surfaces (SAS). The prototype discussed here was a CVE and so the SAS will not be discussed further (but see [55,56], for more details). The bespoke CVE was a 3-D virtual space, which could be navigated in real time, and allowed more than one user to interact with the scene and each other. The focus on collaborative technology adds to the small, but growing literature that explores the potential benefits of encouraging children with autism to interact with peers and/or teachers via technologies that promote engagement and interaction in different ways [57–61]. Such approaches move beyond the limitations of a one-user/one-computer set-up and didactic learning approaches common in earlier studies (e.g. [62, 63]) and have shown promise in supporting children to work together on tasks.

The 3-D affordances of virtual environments have been argued to support "more effective collaborative learning" [64, p. 10] than 2-D programmes. Indeed, Dickey [65, p. 122] suggests that there is "compelling evidence of the potential that graphically rich three-dimensional settings provide for constructivist learning activities". Parsons and Mitchell [66] also argue that, for children with autism specifically, VEs can be designed to incorporate both behavioural and cognitive approaches to learning, thereby aligning with the project's theoretically-informed aim to support both aspects. Additionally, CVEs support different users to share the same virtual space but from individual computers, which means that each user has a unique perspective on any shared virtual scene or interaction [65]. In other words, in order to connect and communicate with others in the same virtual space, users need to take into account that others will see and experience the scene differently from themselves. Given the fundamental importance of communicative perspective-taking for interpreting language appropriately and interacting socially [67,51] this is an affordance of a CVE that enables interactions to be designed to target and strengthen skills in this area for children with ASD. Finally, given the conceptual importance of scaffolding for supporting learning, CVEs allow for prompts to be designed into the structure of the game itself as well as for facilitation to be provided by peers and teachers physically sat alongside children and/or interacting with them in the CVE [68].

Indeed, teacher's views about how and when such facilitation could be provided for children formed a strong part of understanding the *Thoughts* and territory of the intended users. Teachers from both special and mainstream schools, as well as children, with and without ASD, were involved throughout the project in a range of learner-centred design activities [14]. These activities informed the look and feel of the *Block Challenge* game, the pedagogical structure of the tasks, as well as how interactions could be supported and rewarded within and around the CVE; for example, teachers and children suggested the use of a reward tool bar where users could collect stars for collaborative interactions (see [69] for more details). Importantly, the project worked in schools from the start and so ensuring that the CVE could run on standard desktop or laptop computers that are frequently used in schools was essential.

3. Implementing the learner-centred design of the Block Challenge CVE

3.1. Description of Block Challenge

The *Block Challenge* CVE was built in DEMON (3-Dimensional Environment for Multiuser simulations[1]), run on standard laptop computers using a mouse for interaction. *Block Challenge* was designed as a two-player CVE game in which children had to verbally communicate and collaborate with, and understand the perspective of, the other child in order to be successful in completing the game. Each player takes a different first-person perspective within the CVE such that they can see and interact with other people in the environment but they always maintain their own perspective within the scene. A screen was used to separate the children to ensure that they focused on the CVE and communicated with their partner via the game (using microphone headsets) rather than face-to-face. A facilitator (teacher or researcher) sat next to each child and had access to guidelines and checklists, which were printed in a manual before and during the session (see Fig. 1).

3.2. Training phase

With the help of a facilitator, children were introduced to "Professor Blocks", a virtual character programmed into the software that provides instructions and feedback on children's performance (see Fig. 1). Children are prompted to navigate through the CVE, to ensure that they understand simple visual perspective-taking (cf. [70]). They also watch a short instructional video about how to play the main game.

3.3. Main task

Pairs of children have to choose and stack virtual dual-coloured blocks together and communicate with each other to establish that the chosen block enables them to match their own target (only seen by themselves) as well as their communication partner's. Each child's colour targets were composed of two block towers and were different to their partner's but children always had the choice to collaboratively select a block with both their colour targets from an array (e.g. Child A needed a red block and Child B needed a yellow block, and the correct block for them to select from an array was the one that was half red and half yellow). After children had selected a block, it appeared in the middle of the room in the incorrect orientation relative to the two children; with the two sides of the block showing the two colours facing both children, rather than with the side with only their target colour facing them. Children then needed to collaboratively rotate the block into its correct orientation. Once rotated into the correct orientation children had to agree whether to 'keep' or 'swap' the block, after which they would receive feedback from Professor Blocks with further instructions if their block or rotation choices were incorrect, and a prompt to communicate with each other to resolve the problem.

There were three levels of difficulty in this CVE prototype: (1) only the two blocks (one for each level of the tower) needed to complete the task with no distracter blocks; (2) the two blocks needed to be successful on the task plus two distracter blocks not sharing any of the target colours; and (3) the two target blocks plus alongside four distracter blocks, each containing one of the target colours, thereby making it more difficult to find and select the blocks that match the needs of both players.

3.4. Pairing and facilitation

Children took part within TD–TD or ASD–ASD pairs. This approach was considered important as part of this study for understanding (a) how TD pairs of children approached the task generally; (b) whether TD pairs differed in important ways in their responses to the task compared to children with ASD; and (c) whether pairs of children with ASD could be supported to effectively interact with each other through the CVE medium. The latter was particularly relevant in the context of educational provision for children with ASD, which often involves ASD-specific group work on social understanding, even in the context of mainstream (general) educational provision (e.g. [71]). In addition, given the importance of scaffolding of understanding taking place within a reasonable zone of proximal development between pairs of children, we did not want to pair ASD–TD pairs initially in case

[1] Both DEMON and the *Block Challenge* CVE were built by COSPATIAL partners at the University of Nottingham, UK.

Fig. 1. Screen shot from *Block Challenge* (left) and equipment set-up (right).

the gap between them in their reciprocal communication was too large and, therefore, the task too demotivating.

Facilitators were provided with a short instruction booklet explaining the purpose of the game and how to support children during their use of it [22,23]. In addition, facilitators received further personal guidance from the research team, explaining their role was to help children with anything that needs clarifying or by giving any prompts above and beyond the program instructions when and where necessary. In cases where children made errors, showed poor perspective taking or displayed non-collaborative behaviours, the role of the facilitator was to prompt children to correct those errors and to help them understand a preferred course of action or why a misunderstanding occurred. Facilitators were encouraged to let children complete the task as independently as possible and to provide support and encouragement, or modelling of appropriate responses, if required. The interactions between pairs of children were intended to be child-led, rather than adult directed; with adults providing a contingent, responsive and supportive role as needed.

4. Small-scale evaluation of the *Block Challenge* CVE

4.1. Participants

Participants were recruited from three mainstream primary schools and one mainstream secondary school in England that had expressed an interest in the project and a willingness to take part. All of the typically children attended one of the primary schools; one pair of children with ASD came from each of the three other schools. The head teacher gave permission for the research to be conducted and for parents and teachers to be asked for their consent for participation. Parents provided informed consent for their children to take part and children were provided with age-appropriate information for assenting to their own participation. The teachers also provided their informed consent to take part. The project was reviewed and approved by the University of Birmingham's Social Sciences ethics committee.

14 children and five facilitators (two teachers and three researchers) took part: six children had an ASD and were aged 10–13 years; eight were typically developing (TD) and aged 7–9 years. All children with ASD were selected for inclusion in the study on the basis of diagnostic information within their Statements of Special Educational Need. Children's parents were asked to complete the Social Communication Questionnaire (SCQ; Rutter, Bailey and Lord [72]) to confirm autism characteristics. Two were not returned but the scores for the remaining four children in the ASD group were 31, 25, 20 and 15 (with scores of clinical significance being 15 or above).

4.2. Procedure

All sessions took place on school premises, in a quiet room away from the child's main classroom and were videotaped for subsequent analysis. Children took part in three sessions in fixed order, each lasting approximately 30 min on separate days, over the course of two weeks. In the first session, all children were assessed for language (BPVS-III; Dunn, Dunn, Styles, and NFER-Sewell [73]) and IQ (WASI; Wechsler [74]). Children in the TD group were matched group-wise to children in the ASD group on verbal mental age (VMA), as assessed by the BPVS. Children with ASD were older than the TD children but otherwise similar in terms of these background characteristics (see Table 1).

In the second session, children's ability to take the perspectives of others was assessed via a standard first-order change of location [75] and second-order ("John thinks that Mary thinks …"; Perner and Wimmer [76]) Theory of Mind (ToM) task. Table 1 shows that all children apart from one child with ASD passed the first-order task, and only 4 children (2 ASD, 2 TD) passed the second-order ToM task. Children's executive function abilities were also assessed via the BADS-C [77], which comprises specific sorting and problem-solving tasks, as well as the DEX-C questionnaire, which asked teachers to rate children's everyday executive behaviours on a 5-point scale from "Never" to "Very Often" (e.g. "Finds it difficult to stop doing something even if he or she knows they shouldn't"). Table 1 also shows that while the children with ASD had more executive difficulties than the TD pairs overall (as would be expected), the children were very similar on the ToM measures, language and IQ. Table 2 shows the breakdown of performance on these background tasks for each child within each pair, along with the total number of moves made by each child and facilitator.

In the third session, children were paired together based on friendship judgements made by the teachers and were supported in using the *Block Challenge* CVE, moving through the training phase and then into the main game. All pairs of children knew each other, and were in the same classes at school.

4.3. Analysis

This descriptive small-scale study aimed to establish whether *Block Challenge* enabled the reciprocal, communicative perspective-taking interactions between children, as well as scaffolding behaviours between teachers and children, that it had been designed to do. A detailed coding system was developed for the child–child interactions using the software Transana [78], based on the approach taken by Mavrou [79–81] who analysed the communication of pairs of children working together on computer-based tasks. Mavrou's [79] codes were inductively modified to reflect the specific features of the *Block Challenge* task, undertaking a line-by-line thematic analysis of the children's verbal and non-verbal "moves", which were then conceptually grouped into collaborative and non-collaborative interactions based on Holt and Yuill's [59] coding of autistic children's interactions on computer-based collaborative

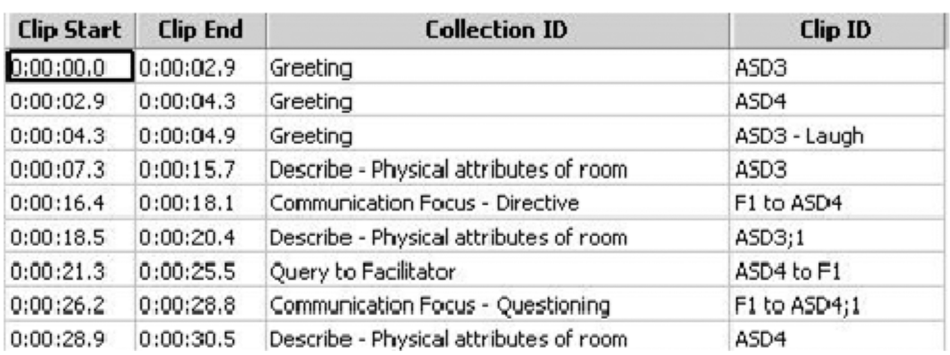
Table 1
Mean and standard deviations for age, language, IQ, and executive function; and number of children passing ToM tasks.

	N		Chronological age	Verbal mental age (BPVS)	BADS-C overall age-scaled score	DEX-C Qu'aire (Out of 80)	Full scale IQ (WASI)	First order ToM	Second order ToM
ASD	6	Mean	11.07	9.03	43.17	42.33	96	5	2
		s.d.	1.05	3.08	14.16	15.51	27.6		
TD	8	Mean	8.04	8.00	54.88	5.14	115	8	2
		s.d.	0.08	0.08	7.92	7.58	9.7		

Table 2
Individual scores for each child on cognitive, language and ToM tasks (1 = pass, 0 = fail) and number of moves taken by each child and facilitators to complete the three levels of *Block Challenge*.

Pair		VMA	BADS	DEX	ToM1	ToM2	Total no. of moves by child	Total no of moves by facilitator
ASD1	Child A	6.01	30	44	1	0	54	105
	Child B	8.07	56	65	1	0	45	88
ASD2	Child C	11.0	55	44	1	1	62	29
	Child D	15.09	57	23	1	1	60	11
ASD3	Child E	8.03	33	27	1	0	113	236
	Child F	5.11	28	51	0	0	117	177
TD1	Child G	7.1	58	0	1	0	33	46
	Child H	7.02	56	7	1	1	32	36
TD2	Child I	9.07	60	20	1	0	32	26
	Child J	8.02	40	[a]	1	0	43	30
TD3	Child K	7.08	56	0	1	1	30	33
	Child L	8.04	56	0	1	0	43	33
TD4	Child M	7.11	52	0	1	0	70	96
	Child N	7.1	50	9	1	0	69	82

[a] Missing data.



Clip Start	Clip End	Collection ID	Clip ID
0:00:00.0	0:00:02.9	Greeting	ASD3
0:00:02.9	0:00:04.3	Greeting	ASD4
0:00:04.3	0:00:04.9	Greeting	ASD3 - Laugh
0:00:07.3	0:00:15.7	Describe - Physical attributes of room	ASD3
0:00:16.4	0:00:18.1	Communication Focus - Directive	F1 to ASD4
0:00:18.5	0:00:20.4	Describe - Physical attributes of room	ASD3;1
0:00:21.3	0:00:25.5	Query to Facilitator	ASD4 to F1
0:00:26.2	0:00:28.8	Communication Focus - Questioning	F1 to ASD4;1
0:00:28.9	0:00:30.5	Describe - Physical attributes of room	ASD4

Fig. 2. Excerpt from time-flow log from Transana showing the line-by-line coding (collection ID column) and the "moves" of children and facilitators (Clip ID column).

tasks. The analysis focused on three main aspects of the interactions:

(i) *Interactional "moves" between the children*: the number of moves that each child took within each of the three levels of *Block Challenge* was counted to provide an indication of how much each child contributed to the interactions. A "move" was defined as a verbal or non-verbal behaviour directed at the other child and represented by the coding of a single line of the transcript (see Fig. 2 for an excerpt of the time-flow of interaction which illustrates the line-by-line coding). The total number of moves can be considered a proxy indicator of reciprocity between the pairs in the sense that the game cannot progress unless children mostly contribute in a reciprocal manner, taking turns to complete each stage of the task. This structure was designed into the game to ensure that children were supported in making reciprocal exchanges. It is difficult to represent fully the exact sequences of interactions between the pairs because of the high total numbers of moves involved; nevertheless, Fig. 2 provides an insight into how moves were represented between children, and also between children and facilitators.

(ii) *Peer–peer communication*: the full coding system used to analyse the communication within the child pairs is shown in Table 3. These codes include verbal and non-verbal behaviours, which were represented separately within the coding scheme (e.g. see 'Accept', and 'Acting with no description'); the majority of codes represented verbal behaviours, reflecting the specific task demands of *Block Challenge*. An independent coder who was not part of the core research team provided an inter-rater check on the coding from one full transcript of one pair of children with ASD; with agreement at 84% (145/172 codes). The fine-grained nature of the coding scheme was intended to discriminate between responses in order to avoid the use of multiple codes for individual behaviours. This high rate of inter-rater agreement in the context of such a detailed coding system suggests that the scheme was successful in this regard, although even stronger reliability and validity could have been demonstrated had inter-rater coding been extended to a wider sample of the data. Unfortunately, time and resource considerations precluded this.

Given that the objective of *Block Challenge* was to support communicative perspective-taking and reciprocity via collaboration, the fine-grained codes were grouped conceptually into behaviours that indicated collaboration and task engagement and those that did not. This grouping was based on Holt and Yuill's [59] coding of autistic children's behaviours in a collaborative computer-based

Table 3
Inductive coding of children's behaviours mapped to behavioural categories from [59].

Initial inductive codes of verbal and non-verbal [NV] behaviours of the children using *Block Challenge*	Example comment or action	Behavioural categories from [59]
Agree	I agree with you … and I agree with myself!	Active other awareness (ACO)—intentional relationship to partner's comment or action
Attention	Getting partner's attention, e.g. by saying their name before speaking	
Co-ordinate play	Verbally co-ordinate actions in CVE: e.g., 1, 2, 3 … rotate!	
Describe—action/intention/decision-making	'So I'm clicking on the red and yellow one'; so I've chosen the red and yellow one'; 'I'm going to click rotate'	
Disagree	I don't think that's the right one'; 'no we need this one'; 'No!'	
Inform	'So I need the yellow one' 'My bottom target is red'	
Instruct	'Click on the pink and yellow' 'Press stop then'	
Invite	'Come on then, let's rotate!'	
Justify	'I need to switch blocks because I'm not happy with the one we picked'	
Offer help	'If we turn the block then you will see the yellow side and I will see the blue side so that's what we need to do'	
Protest	'Why do you want to switch the block? I don't want to!'	
Question—task relevant	'What colour do you need?'	
Suggest	'Should we rotate the block?'	
Accept [NV]	Non-verbal version of agree e.g. clicking on the rotate button in response to: "we need to rotate the block"	Attentional other awareness (ATO)—related to but not contingent on the other's action
Acknowledge	OK	
Confirm	Ok, so we need a yellow and a blue one	
Quiet/softly spoken	Speaks/answers in a quiet voice that may not heard/understood	
Sharing reasoning	Reasoning/problem-solving out loud or explaining an action or a comment/instruction/suggestion.	
Acting with no description [NV]	Acting within the CVE without any communication with partner	Approach to task (APT)—task-related behaviours not directed at the other child
Answer—task relevant	Simple factual answer to a task relevant question. E.g., I need a blue	
Confused	'Umm, I'm not sure …'	
Literal	Uses information literally rather than within context	
Reading	Reading out the instructions provided by Professor Blocks within the CVE	
Shows enjoyment	Whilst playing task. E.g., laughing or making positive comment about task	
Talks about feelings	How they feel in the given situation: e.g. 'I'm really enjoying this', 'this is stressful'	
Uses facilitator feedback	Acts on facilitator feedback or takes it into account when performing task e.g. 'She needs that one (points to block with mouse) and that one' (following a question from facilitator: why don't you find out what xxxx needs?)	
Describe—physical attributes of room	No purpose to description other than to tell partner what s/he can see in the CVE room (exercise at the beginning of game)	
Greeting	Hello!	
Positive feedback	'Well done!' 'We did it!'	
Distracted [NV]	Is distracted from the game and as a consequence does not seem to pay full attention to the communication with partner (does not respond when spoken to or is slow to respond).	Withdrawal from task (WFT)—non-task related behaviours
Does not offer info in return/does not ask for info in return [NV]	Child A has offered or asked for relevant information ('I need a yellow' or 'What colour do you need?') and Child B does not offer the corresponding relevant information; stays silent.	
Ignore	Ignores specific communication made by partner by responding with a non-related verbal response.	
Ignore facilitator feedback [NV]	Ignores feedback from the facilitator that would help resolve an issue that has arisen within the game (such as collaboration/communication/perspective taking).	
Off-task behaviour	Chasing each other's avatars within the CVE or commenting on an aspect of the game that is not related to the completion of the task. e.g. (Looks at the blocks) 'Oh my God' (moves avatar side to side) 'I'm a block!'	
Uncooperative [NV]	Refuses to play along or makes it difficult for partner to play game e.g. looking in different parts of the room rather than at the block.	

task. Their approach was adopted because Holt and Yuill's [59] analysis specifically sought to capture the interdependent nature of the interactions between children with ASD in the completion of a collaborative computer-based task, and separate these from behaviours that did not support task completion or were not reliant on co-operation from the other child. The present study, in line with Holt and Yuill [59], aimed to reflect that some behaviours were intentionally targeted at the other child in the paired task, while other behaviours were related to the technology or to the task, or to the facilitator, but not directly to the peer. In other words, it was important to show that children could still be co-operative and task-focused without direct communication with each other, including taking into account the support received from the facilitator. Thus, there was a strong conceptual alignment between Holt and Yuill [59] and the present study, not least in seeking to capture the capabilities and active engagement of the children, rather than focusing on absences or deficiencies in behaviours. Holt and Yuill's [59] coding was mostly based on non-verbal behaviours due to the nature of their task and the inclusion of less verbally able participants. The extension of their coding scheme to the present study, focusing on mostly verbal behaviours with more able participants, also represents a valuable contribution to knowledge.

The conceptual categorisation of the fine-grained coding was discussed and checked with Holt and Yuill directly (personal communication). Specifically, the fine-grained codes were grouped into four main categories (see Table 3):

- *Active other-awareness (ACO)*—indicates an intentional, contingent relationship to partner's comment or action relating specifically to successful task completion e.g. explicitly co-ordinating actions to complete the task;

- *Attentional other-awareness (ATO)*—related to but not contingent on the other's action with the aim of further progressing or completing the task e.g. clicking agree but without explicit acknowledgement or further action;
- *Approach to task (APT)*—task-related but not directed at the other child e.g. navigating the screen or task buttons on own screen;
- *Withdrawal from task (WFT)*—not task-related e.g. showing frustration, ignoring the other child, disrupting the task, moving around the virtual space without trying to complete the task successfully.

(iii) *Teacher facilitation*: each facilitator move (communication directed towards the child) was counted and coded on a line-by-line basis using the transcript and the video footage, again taking an inductive approach to describe how the facilitators were supporting children's engagement with the task and each other (see Table 4). Independent inter-rater coding for one full transcript showed agreement of 95% (112/118 codes). The utterances made by children and facilitators were single statements or questions that could be coded in one category and these are presented as frequencies below.

5. Results

The results are presented according to the three main categories for analysis introduced in Section 4.3. First, the data that shows the reciprocity of communication between the pairs of children by analysing their interactional "moves" during the game; second, the within-pair communication between the children analysed using Holt and Yuill's (2014) collaboration categories; and third, the amount and nature of facilitation provided by teachers according to frequency and purpose of the instructions or comments.

5.1. Reciprocity of the children

Fig. 3 shows the total number of moves taken by each pair to complete the three levels of the task. The ASD pairs tended to take more moves than the TD children overall (451 vs. 352 respectively), although TD pair 4 took more moves than ASD pairs 1 and 2. Closer examination of the interactions in TD pair 4 showed that they tended to use each other's name to establish initial attention ("Jenny?" "Yeah …") before proceeding with the task ("I need to rotate") rather than a fundamental difficulty with the task. ASD pair 3 took many more moves to complete the task compared to the other pairs. Comparing the frequency of moves taken within each pair there were no significant differences for either the ASD or TD children, according to chi-squared analyses. This suggests that children within the pairs were contributing equally to the task. There was a general trend in most of the pairs (apart from ASD3 and TD2; see Fig. 4) for the number of moves to decrease as the game became more difficult over the levels, suggesting that communication became more efficient as children became more familiar with the task.

5.2. Peer–peer communication

Fig. 5 summarises the average total number of behavioural codes for each group based on Holt and Yuill's [59] four main categories, and Table 5 presents the number of, and average, codes per pair and per group, according to each category. The overall pattern of responses across the four main categories was similar for both groups (Fig. 5), suggesting that the pairs of children approached the task in similar ways. In all categories, the ASD pairs had higher frequencies overall than the TD pairs, with the majority of behaviours in the Active other-awareness (ACO) and Approach to Task (APT) categories (Table 5). The ASD pairs also showed more off-task behaviour with higher frequencies in the Withdrawal from Task (WFT) category. There were some slight variations from this overall pattern within some pairs (see Table 5), for example ASD3 were less communicative with each other relative to the other ASD pairs, and TD4 were more communicative with each other, relative to the other TD pairs (see also Section 5.1). Nevertheless, the overall pattern of higher frequencies in the ASD group remained even when the number of moves was controlled for. The overall ratio of collaborative/on-tasks (ACO+ATO+APT) to non-collaborative/off-task (WFT) behaviours across the pairs in each group was 38:1 in the TD group and 9:1 in the ASD group. This suggests that even though the ASD pairs showed high levels of engagement with each other, and the task, they were less collaborative and task-focused than the TD pairs overall as a proportion of the total number of behaviours observed.

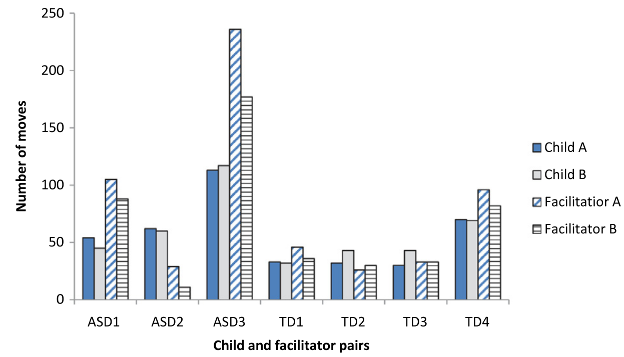


Fig. 3. Total number of moves by children and facilitators within each pair.

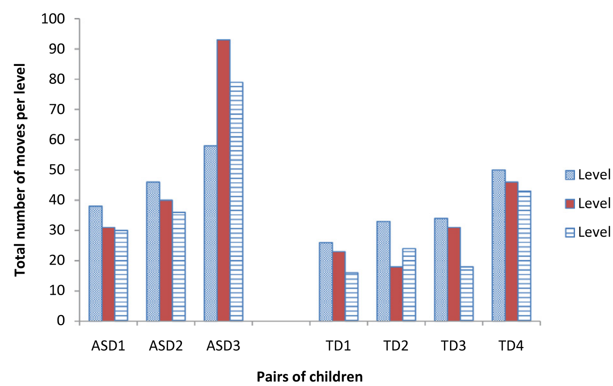


Fig. 4. Number of moves taken within each pair across the three levels of the game.

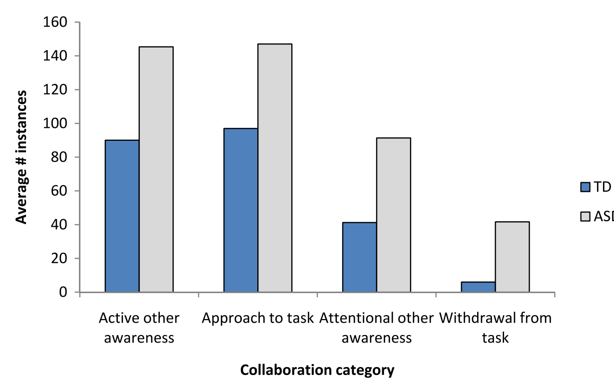


Fig. 5. Average number of behavioural codes for the ASD and TD groups (based on Holt and Yuill's [59], categories).

Table 4
Codes of verbal interactions between facilitators and children.

Facilitator to child interactions	Example
Brings child's attention back to task	'Sam, look at what Professor Blocks is asking you to do'
Clarifying directive	Giving an instruction and explaining it e.g., 'So, you need to click on the brown and yellow block because you need brown and Johnny needs yellow'; 'If you say his name, he will know to pay attention to you'
Communication focus	Scaffolding the communication. E.g., 'Can you ask Johnny what he needs?' 'Did you hear what Sam just said?'
Concept focus	Checking/explaining the underlying concepts i.e. that the conversational partner has a different perspective on the task and different needs for successful completion e.g. 'So, why is Johnny asking for a yellow block?' Also explaining the concept of collaboration (not just perspective-taking) e.g., 'So you need ask Sam what colour he needs and tell him what colour you need so that you can choose the right block for both of you'
Modelling communication	Telling the child exactly what to say to partner e.g., 'why don't you say 'Sam, what's the colour of your block on the bottom?'
Praise	'Well done! You told Sam which block you needed'
Procedural focus (Including helping to read/reading)	Reading task instructions from Prof. Blocks on the screen or providing information about interacting with the game: 'So what does Professor Blocks tell us to do … (reading instruction from the screen)' 'Press A to move on …'
Task focus	'What colour do you need?' 'So you need blue, what do you need to do next?'

Table 5
Frequencies and pair, and group, mean frequencies for collaboration coding.

Frequencies	Typically developing (TD) pairs				TD group	ASD pairs			ASD group
	1	2	3	4	$\bar{x}$	1	2	3	$\bar{x}$
Active other awareness (ACO)	68	83	89	120	**90**	95	218	123	**145.3**
Approach to task (APT)	106	79	52	151	**97**	173	205	63	**147**
Attentional other awareness (ATO)	56	25	24	60	**41.2**	74	175	25	**91.3**
Withdrawal from task (WFT)	5	5	4	10	**6**	60	39	26	**41.6**
Pair $\bar{x}$	**58.7**	**48**	**42.2**	**85.2**	**58.6**	**100.5**	**159.2**	**94.8**	**106.3**

5.3. Teacher facilitation

The number of moves taken by teachers to support children's responses is shown in Fig. 2. A relatively high level of facilitation was provided for ASD pairs 1 and 3 compared to the others, while ASD2 received the lowest level of facilitation overall and pair TD4 received more facilitation relative to the other TD pairs. It is interesting to note in this context that both children in ASD2 passed the second-order ToM task, while both children in TD4 failed the second-order ToM task (Table 2), though a low level of facilitation was also observed in TD2, both of whom also failed the task. Fig. 6 shows the nature of facilitation provided across the pairs in each group based on the interpretive codes shown in Table 3. Mostly, the overall pattern of facilitation for the TD and ASD pairs was similar, although frequencies were generally higher in all categories for the ASD group. It is noticeable that more facilitation was provided overall for the ASD pairs in the Task and Procedure categories, as well as in the Concept and Communication categories, relative to the TD pairs.

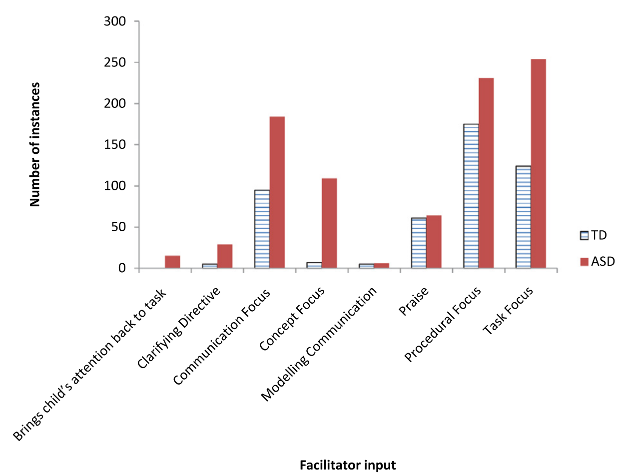


Fig. 6. Nature and frequency of facilitator input for ASD and TD pairs.

6. Discussion and conclusions

The results of this descriptive, proof-of-concept study showed that pairs of children with ASD and pairs of TD children communicated with each other throughout the *Block Challenge* task and in mostly similar ways. The children with ASD made sustained endeavours to communicate with their partners during their use of *Block Challenge* and were as reciprocal in their communication as the TD children. Indeed, the pairs of children with ASD made more communicative moves to their partners than the TD children, even when the total number of moves was taken into account. It could be that the ASD pairs maintained communication because they did not or could not make assumptions about their partner's knowledge in the way that the TD children did. For example, once they quickly became used to the game, the TD children sometimes acted after reading the instructions from the screen without necessarily communicating with their partner, possibly because they found the task too easy and/or made assumptions about what their communication partner did or did not know about the target. Anecdotally, when talking about the task following the session some of the TD children suggested that they found the task too easy and would have liked it to be harder, but this would be something worth investigating specifically in future studies. Moreover, given the small-scale nature of the study and the small numbers of children involved it is not possible to confirm the stability of any putative differences between pairs and so results should be interpreted with caution.

By contrast, some of the children with ASD struggled (as expected) with the conceptual and communicative demands of the task, compared to the TD children, despite being matched with them on verbal ability. Reflecting these difficulties, the ASD pairs of children on average received more than double the input from facilitators sat alongside them compared to TD pairs and made more moves to get to the same successful outcome compared to most of the TD children. In addition, even when taking into account the total number of moves made within each pair, the ratio of collaborative, task-focused behaviours to task withdrawal behaviours was much higher for the children with ASD, compared to the TD pairs. This suggests that communication between the ASD pairs was less efficient, or at least less targeted and effective, compared to the TD children, corresponding with similar findings on different communication tasks [82,67]. Nevertheless, there was a trend in most pairs of children in our study for the number of turns to decrease across the three levels of the game despite the increasing difficulty of the task, suggesting that a reduction in the number of turns could signal an improvement in children's targeted communication as they became more familiar with the task.

These findings are encouraging for at least two reasons: firstly, they suggest that *Block Challenge* seems to be effectively and appropriately targeting the specific communicative and conceptual challenges that we planned from the start and secondly, that – with supportive input from facilitators – children with ASD can, nevertheless, complete the tasks successfully despite their well-documented difficulties in social reciprocity (see [51] for a review). Successfully completing the *Block Challenge* task requires that children take into account the perspective of their communicative partner because it was designed in such a way that the task could not be completed unless children did this. Thus, the fact that all pairs of children completed the three levels of the game, albeit with varying degrees of help from the facilitators, demonstrates that they were able to consider their partner's perspective even though the majority (in both the TD and ASD pairs) failed the standard second-order ToM task. Therefore, *Block Challenge* seems to provide an educational context in which social communication, perspective-taking and reciprocity can be encouraged and practised between ASD peers and scaffolded effectively by teachers, in support of previous research [83–85]. This demonstrates that *Block Challenge* appears to be pitched at a level that allows children with these ability profiles to be successful (with support) but which also effectively targets core difficulties in social communication, in line with our planned design approach.

There was a tendency for some of the children with ASD to show more non-task related behaviours (categorised as 'Withdrawal from task') than the TD pairs within their use of the CVE. This is consistent with the findings of Parsons, Mitchell and Leonard [86] who showed that a subset of children with ASD – with lower verbal and executive abilities – tended to be more exploratory and less task-focused in their use of a single-user VE compared to TD children. Although the numbers are small, and so this interpretation is necessarily cautious, some of the children with lower verbal and executive abilities, who also failed the second-order ToM task, showed these behaviours in the present study (pairs ASD1 and ASD3). Perhaps unsurprisingly, these were also the children who received the most support from facilitators. This reinforces the importance of documenting the background profiles of the children who struggled the most on these tasks, as well as the pedagogical roles that the facilitators played in helping children to complete the tasks successfully [61]. This also suggests that a case study approach to investigating children's performance on the task would be valuable in future studies so that background characteristics and context can be clearly represented (cf. [87]). Such an approach could also be applied to exploring the interactions between different pairs of children (e.g. mixed ASD + TD) to see whether *Block Challenge* could be useful for supporting communication in inclusive settings.

As a small-scale study there are limitations that need to be acknowledged. Although most parents completed the SCQ to confirm their child's autism characteristics, two parents did not return this information and so the data were incomplete in this regard. We had confirmation from formal school records regarding the professionally identified needs of the children however, the strongest confirmation can be obtained from the completion of the Autism Diagnostic Observation Schedule (ADOS; Lord et al. [88]). It was also not possible to ascertain background information about the children that may influence their interaction with the CVE, e.g. fine-motor skills, visuo-spatial abilities, and technology use more generally. Finally, while the inter-rater coding provided a good indication of reliability using a detailed coding scheme, it would have been even stronger if a larger proportion of the data had been checked.

Overall, this study suggests that this novel CVE technology is appropriate and motivating for children with ASD and, therefore, establishes a valid proof-of-concept basis for using *Block Challenge* as a learning intervention between higher-functioning pairs of children, focusing on collaboration and reciprocity of communication. A larger-scale study incorporating the technology has been undertaken and will be reported in due course. The 3T design approach taken, incorporating Theory, Technology and Thoughts, was successful in supporting the design of an ASD-specific technology and offers a helpful framework for informing the design and development of future educational technologies in this area.

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