Autism
http://aut.sagepub.com/

The uses of cognitive training technologies in the treatment of autism spectrum disorders

Sam V Wass and Kaska Porayska-Pomsta
Autism published online 15 October 2013
DOI: 10.1177/1362361313499827

Review

autism

Autism
0(0) 1–21

DOI: 10.1177/1362361313499827
aut.sagepub.com
SAGE

The uses of cognitive training technologies in the treatment of autism spectrum disorders

Sam V Wass[1] and Kaska Porayska-Pomsta[2]

Abstract

In this review, we focus on research that has used technology to provide cognitive training – i.e. to improve performance on some measurable aspect of behaviour – in individuals with autism spectrum disorders. We review technology-enhanced interventions that target three different cognitive domains: (a) emotion and face recognition, (b) language and literacy, and (c) social skills. The interventions reviewed allow for interaction through different modes, including point-and-click and eye-gaze contingent software, and are delivered through diverse implementations, including virtual reality and robotics. In each case, we examine the evidence of the degree of post-training improvement observed following the intervention, including evidence of transfer to altered behaviour in ecologically valid contexts. We conclude that a number of technological interventions have found that observed improvements within the computerised training paradigm fail to generalise to altered behaviour in more naturalistic settings, which may result from problems that people with autism spectrum disorders experience in generalising and extrapolating knowledge. However, we also point to several promising findings in this area. We discuss possible directions for future work.

Keywords

autism, technology-enhanced behavioural interventions

Introduction

> […] you're so patient, but a computer is even more patient, computers are great in comparison to you. When I was five I could already write and do sums, but nobody noticed because […] I was scared of people, because I was unable to speak.[1]
>
> (Sellin, 1993)

Insofar as the bewildering heterogeneity of neurological and histochemical abnormalities associated with autism spectrum disorders (ASDs) can combine to cause a single, autistic cognitive phenotype, this is found in the tendency of individuals with ASD to prefer systematisable, rule-based situations (Baron-Cohen, 2002; Cohen, 2007). Individuals with ASD commonly report that they enjoy using technology, since this requires attention to detail, is generally highly predictable and is affect-free per se (El Kaliouby et al., 2006; Picard, 1997, 2009; Picard et al., 2004). The past two decades have seen an explosion of activity from individuals with ASD using technology as a medium to interact online, with an Autism Liberation Front active on Second Life,[2] countless online autism community groups[3,4] and online video diaries from individuals with autism that have reached almost a million views.[5]

The fact that so many individuals with ASD enjoy technology and technology-mediated interaction makes it a perfect medium for providing interventions; people always perform better in situations in which they feel secure and motivated (Dweck, 1986). Furthermore, there are numerous practical advantages (Bishop, 2003; Murray et al., 2005). The heterogeneity of symptom severity in people with ASD can pose practical difficulties for care providers (Myers et al., 2007); technology has the potential to provide individually tailored interventions that are suitable for a wide variety of abilities (Bishop, 2003). Some technologies, such as cheap imitative robots or gaze-contingent environments, are being developed for potential use even by severely impaired individuals, with need for supervision only from a parent or care-giver. Technological interventions allow the user to work at different speeds and locations, and never lose patience

[1]Medical Research Council Cognition and Brain Sciences Unit, UK
[2]Institute of Education, London Knowledge Lab, UK

Corresponding author:
Sam V Wass, Medical Research Council Cognition and Brain Sciences Unit, 15 Chaucer Road, Cambridge CB2 7EF, UK.
Email: sam.wass@mrc-cbu.cam.ac.uk

with the frequent repetition that many people with ASD desire (Wilkinson et al., 2008). This offers the opportunity to reduce some of the crippling personnel costs associated with autism care (Foundation for People with Learning Disabilities, 2007). While the initial development costs of technological interventions can be high, the scalability costs are comparatively low (Bishop, 2003).

Technology is being used in increasingly varied pedagogical contexts, both as assistive technologies and as tools for helping us understand better user motivation (Arroyo and Woolf, 2005; Cramer et al., 2011; Du Boulay, in press; El Kaliouby and Robinson, 2004; Keay-Bright, 2006; Kientz, 2012; Kientz et al., 2009; Yannakakis and Hallam, 2006). In this review, we focus on uses of technologies in ASD that have an explicit cognitive training component, that is, technologies that aim to improve performance on some measurable aspect of behaviour. This can include both *explicit* knowledge (e.g. 'what does the word "umbrella" mean'?) and *implicit* knowledge (e.g. an individual's ability to cope with sensory overload). Our discussion is organised around three specific and discrete learning goals: (a) emotion and face recognition, (b) language and literacy and (c) social skills. This structure overlaps with, but is not identical to the three core components of ASD – social skills, communication and restricted behaviours (American Psychiatric Association (APA), 1994); restricted behaviours are not included because very few technological interventions have addressed them directly, although some have indirectly (see, for example, Hetzroni and Tannous, 2004).

Inclusion criteria

Studies were identified for inclusion in this review following searches conducted on PubMed and Google Scholar using the following search terms: 'technology and autism', 'software and autism', 'virtual reality and autism' and 'robotics and autism', as well as from relevant articles (e.g. Kientz et al., 2007; Parsons and Cobb, 2011; Pennington, 2010; Wainer and Ingersoll, 2011). Our inclusion criteria for this review were as follows:

- Presence of an explicit cognitive training component, that is, studies that aim to improve individuals' performance on some measurable aspect of behaviour by presenting training tasks in which the difficulty of the task varies contingent on the performance of the individual (Green and Dunn, 2008).
- Delivery of the training largely mediated by computer (including mobile computers and robotics), and requiring only a technician or parent to be present during the administration of the intervention. Interventions that additionally require a trained clinician to be present for each training session were excluded (e.g. video modelling (reviewed in Di Gennaro Reed et al., 2011) and neurofeedback (e.g. Kouijzer et al., 2009)
- Inclusion of an evaluation study to assess the effectiveness of the intervention. These do not include single case studies.

To our knowledge no study fitting our inclusion criteria has been excluded, with two exceptions. First, when several articles have been published by the same research group about a particular intervention, only one representative article – the one carrying the largest scale intervention trial – has been summarised in Table 1. Second, we have not included all the computer tutors for literacy that are available for individuals with ASD. In this area a comprehensive specialised review has recently been published by Pennington (2010); this covers a large number of studies that are technologically similar. Here, we include only a representative selection of these studies, and refer interested readers to Pennington (2010).

Evaluating the effectiveness of the intervention

The following assessment methods are typical for cognitive training interventions across all research fields (Green and Dunn, 2008): a group (as homogenous as possible) is identified, whose performance is assessed at pretest. Half of this group is then randomly assigned to receive the intervention (the trained group); the other half (the control group) ideally attends the same number of intervention visits and receives an *ersatz* intervention. Finally, the performance of all individuals is assessed again (post-test). If the group that received training has improved at post-test relative to pretest more than the control group, then it is judged that the improvement is attributable to the training that was administered. It is desirable for the individuals participating in the study, as well as parents and researchers administering the study, to be blinded as to group allocation, in order to preclude any possibility that expectation of change might influence outcomes.

Studies in which the control group receives an *ersatz* intervention are preferable to studies in which the control group receives no treatment, because research has shown that the expectation of improvement can, by itself, substantially change behaviour (the placebo effect; for example, Beauregard, 2007). Furthermore, in a 'no treatment' control group design, the trained group will have received more total training/testing sessions by post-test; this risks substantially biasing post-test performance. Finally, although several studies included in this review have included a typically developing (TD) trained group, we consider the inclusion of such groups to be substantially less informative than the inclusion of a non-trained ASD control group.

Table 1. Summary of the studies featured in this review (each study is split across two pages).

Authors	Title	Year	Specific target	Description of training	Training period	Pre- and post-tests	*N*–trained subjects
Bauminger-Zvieli et al.	Increasing social engagement in high-functioning children with ASD using collaborative technologies in the school	2012	Social skills	Two computer programs (one tabletop and one laptop) designed to teach social conversation based around principles of Cognitive Behavioural Therapy	12 45-min lessons	(a) Problem-solving and concepts clarification measures; (b) assessment of Theory of Mind; (c) observation during a shared drawing task	22
Bernard-Opitz et al.	Enhancing social problem solving in children with autism and normal children through computer-assisted instruction	2001	Social skills	Animated scenes representing social problems	10 sessions (do not say how long)	Only report on within-game performance measures	8
Bölte et al.	The development and evaluation of a computer-based program to test and to teach the recognition of facial affect	2002	Emotion recognition	Pictures of faces	2 h per week for 5 weeks	Ratings from an independent library of faces and emotions	5
Duquette et al.	Exploring the use of a mobile robot as an imitation agent with children with low-functioning autism	2008	Imitation	Interactive games with a robot	Three sessions per week over 7 weeks	Video-coded imitation of facial expressions, body movements and familiar actions	2
Escobedo et al.	MOSOCO: a mobile assistive tool to support children with autism practicing social skills in real-life situations	2012	Social skills	Mobile augmented reality application, containing interactive features to encourage eye contact and other social skills	25 min per day for 7 weeks	Video interviews	3
Faja et al.	Becoming a face expert: a computerized face-training program for high-functioning individuals with autism spectrum disorders	2008	Emotion recognition	Black and white photographic stimuli accompanied by explicit rule-based instruction	Up to 8 sessions lasting 30 min to 1 h	Standardised measures of face processing; self-report; experimental measure of configural vs featural processing	5
Feil-Seifer and Mataric	Robot-assisted therapy for children with autism spectrum disorders	2008	Imitation	Interactive games with a robot – robot either responded interactively (blowing bubbles on a button press) or not (blowing bubbles at random)	Do not report	Video-coded interaction with the robot	4
Golan et al.	Enhancing emotion recognition in children with autism spectrum conditions: an intervention using animated vehicles with real emotional faces	2009	Emotion recognition	DVD for home use, also a consolidation information pack for parents	At least three episodes per day for 4 weeks.	Emotional vocabulary; familiar close generalisation (familiar situations from the series to facial expressions of familiar characters from the series); unfamiliar close generalisation (novel situations with novel situations from the transporter characters); novel situations with novel expressions using a selection of human non-transporter faces	20

(Continued)

Table 1. (Continued)

Authors	Age (in years)	Diagnostic criteria	Controls (also ASD unless stated)	Improvements within the training paradiagm	Generalised improvements at trained task	Transfer to other tasks
Bauminger-Zvieli et al.	Mean 9.8 (standard deviation = 10.7)	ASD	None	Not reported	✓ Improvements on concept clarification and problem-solving, some improvement on ToM	✓ Some improvements on social engagement
Bernard-Opitz et al.	6–8	HFA	None (8 TD also took part in training)	✓		
Bölte et al.	16–40	HFA/AS	5 – no treatment	✓		
Duquette et al.	5	LFA – no language	2 underwent a matched number of sessions with a human mediator	(✓) Increased shared attention, increased imitation of facial expression. But other measures, for example, imitation of body movements, not improved	×	
Escobedo et al.	8–11	ASD	None	✓ Videoed behaviour and coded changes, for example, in time spent interacting while the technology was in use		
Faja et al.	12–32	HFA	5	✓	× Although do report differences in sensitivity to configural relationships	
Feil-Seifer and Mataric	2–12	ASD	None	✓ More interactions when the robot was responding contingently	✓	
Golan et al.	4–7	ASD	18 ASD, 18 TD (NB just did pre- and post-test)	✓	✓ Large effect sizes for all measures	
Golan and Baron-Cohen	Adults	AS/HFA	Exp 1 (N = 22 ASD, 28 TD) – just pre–post; Exp 2 (N = 13 ASD) – undertook social skills course	✓	×	
Grynszpan et al.	12.1	HFA	None (10 TD subjects also trained)	✓ Trained improvements greater in the no-face condition	(✓) Although pre–post task was very similar to training set	
Grynszpan et al.	13–31	HFA	None (14 TD also trained)	(✓) Gaze-contingent manipulation lead to altered eye movement behaviour in TD, weaker changes in HFA group	× No effects of gaze-contingent manipulation on comprehensibility of ambiguous sentences reported	

Table 1. (Continued)

Authors	Title	Year	Specific target	Description of training	Training period	Pre- and post-tests	*N*–trained subjects
Golan and Baron-Cohen	Systemizing empathy: teaching adults with Asperger syndrome or high-functioning autism to recognize complex emotions using interactive multimedia	2006	Emotion recognition	Silent movie clips, voice clips, written descriptions (separate modalities)	Minimum of 10 h over 10 weeks	(a) Faces and voices included in the intervention but presented using different software; (b) faces and voices not included in the invention; (c) clips from feature films	Exp1 – 19, Exp2 – 13
Grynszpan et al.	Multimedia interfaces for users with high functioning autism: an empirical investigation	2008	Social skills	Text-based software that trained subjects to understand dialogues that contain pragmatic subtleties, sometimes with a static computer-generated face and sometimes not	13 sessions over 3 months (do not report how long each session was)	Comprehension of dialogue that contained pragmatic subtleties (NB a different version of the training software)	10
Grynszpan et al.	Self-monitoring of gaze in high functioning autism	2012	Eye gaze behaviour	Gaze-contingent feedback (blurring of screen except for an area around the focal point of the participant) during administration of Avatar-based single-trials in which sentences were spoken that could be interpreted in two distinct ways	Single session – 20 trials without gaze-contingent feedback, 20 with, 20 without	–	13
Herrera et al.	Development of symbolic play through the use of virtual reality tools in children with autistic spectrum disorders: two case studies	2008	Symbolic play	VR showing imaginative transformations	Twenty-eight 20–30 min sessions over 2.5 months	Behavioural assessment of functional play and pretend play	2
Hetzroni and Tannous	Effects of a computer-based intervention program on the communicative functions of children with autism	2004	Echolalia	Structured one-on-one play environment requiring comprehension of recorded spoken language	18 sessions, 10–25 min per session	Recorded the child's behaviour in school, video-coded for echolalia	5
Holsbrink-Engels	Using a computer learning environment for initial training in dealing with social-communicative problems	2001	Social skills	Software designed to teach social-communicative problem-solving (e.g. giving negative feedback to employees)	11 sessions (do not say how long)	Other computer-presented assessments of social-communicative problem-solving	20
Josman et al.	Effectiveness of virtual reality for teaching street-crossing skills to children and adolescents with autism	2008	Crossing the road	VR exercises on road safety	Eight 10–30 min sessions	Video-taped participants crossing a street in a protected area	6

(Continued)

Table 1. (Continued)

Authors	Age (in years)	Diagnostic criteria	Controls (also ASD unless stated)	Improvements within the training paradiagm	Generalised improvements at trained task	Transfer to other tasks
Herrera G et al.	8–16	ASD	None	✓	(✓) Improvement in structured pretend play reported, but no statistics	(✓) Parental report of generalised improvements in 1 child
Hetzroni and Tannous	8–12	ASD	None	N/A	✓	
Holsbrink-Engels	18–28	ASD	None (21 TD also received an instructional program without computer-based role-plays)	✓	(✓) But pre–post tests very similar to trained set	
Josman et al.	8–16	ASD	None (6 TD also trained)		(✓) Report that 3 of 6 showed improvements, no statistics reported	
Jung et al.	5–6	ASD	None (20 TD subjects also trained)	✓		
Lacava et al.	8–11	AS	None	Not reported	✓ Improvement on all measures administered	
Massaro and Bosseler	8–13	ASD	(Within-subjects design)	✓ More learning occurred with the Avatar than without	N/A	N/A
Mitchell et al.	14–16	ASD, AS	Within-subjects design (3 video assessment sessions; half the subjects did VE training between video session 1 and 2, others between video session 2 and 3)	(✓) Several instances of virtual environment improving the decision about where to sit; also instances of improvements in social reasoning		
Moore et al.	8–16	Do not report	None	✓		
Moore and Calvert	3–6	Do not report	7 (did similar behavioural treatment drill)	✓ Also greater than behaviour package	N/A	N/A
Piper et al.	12.75 (standard deviation = 1.04)	mixed ASD/AS/other	None	✓ Conversation analysis of within-game dialogue		
Rajendran and Mitchell	23	AS	2 subjects with behavioural and emotional difficulties also did training		(✓) No improvements on Vineland interpersonal scales; one subject showed improvements at WCST	
Sansosti and Powell-Smith	6–10	AS/HFA	None	✓	(✓) (1 of 3 subjects) – social communicative skills coded from videoed behaviour	
Schlosser and Blischak	8–12	'mild autism'	None	✓ Although no statistics reported	Tested generalisation to novel words, but no stats	N/A

Table 1. (Continued)

Authors	Title	Year	Specific target	Description of training	Training period	Pre- and post-tests	*N*–trained subjects
Jung et al.	The application of a sensory integration treatment based on virtual reality-tangible interaction for children with autistic spectrum disorder	2006	Sensory Integration Therapy (see notes on Dawson and Watling, 2000)	VR with three components, coordination ability, social skills training, sensory integration therapy	10 h (do not say how long)	None	11
Lacava et al.	Using assistive technology to teach emotion recognition to students with Asperger syndrome	2007	Emotion recognition	Same as Golan et al., 2006	Average of 10.5 h over 10 weeks	Recognising emotions from faces and voices	8
Massaro and Bosseler	Read my lips: the importance of the face in a computer-animated tutor for vocabulary learning by children with autism	2006	Vocabulary learning	Avatar, pictures, recorded sounds, spoken responses	Do not report	Vocabulary assessment tests	5
Mitchell et al.	Using virtual environments for teaching social understanding to 6 adolescents with autistic spectrum disorders	2007	Social skills	Scaffolded virtual environment at graded difficulty levels. Subject had to choose an appropriate place to sit	1.5 h	Showed videos of a café or bus, participants had to judge where to sit	6
Moore et al.	Collaborative virtual environment technology for people with autism	2005	Emotion recognition	Avatar (NB only 4 emotions – happy, sad, angry and frightened)	Do not report	Only tested within-game performance	34
Moore and Calvert	Brief report: vocabulary acquisition for children with autism: teacher or computer instruction	2000	Vocabulary learning	Word teaching drills accompanied by small animations	About 10 min per day for 5 days	Retention of taught words; visual attention; reported self-motivation	7
Piper et al.	SIDES: a cooperative tabletop computer game for social skills development	2006	Social skills	Tabletop computer game encouraging turn-taking and other social skills	Single session	None	8
Rajendran and Mitchell	Computer mediated interaction in Asperger's syndrome: the Bubble Dialogue program	2000	False belief	Interactive cartoon-strip encounters presenting versions of false belief situations	1 h per week for 6 weeks	Vineland Adaptive Behaviour Scales; Wisconsin Card Sorting Test (WCST)	2
Sansosti and Powell-Smith	Using computer-presented social stories and video models to increase the social communication skills of children with high-functioning autism spectrum disorders	2008	Social skills	Computer-presented social stories and video models	Do not report	–	3

(Continued)

Table 1. (Continued)

Authors	Age (in years)	Diagnostic criteria	Controls (also ASD unless stated)	Improvements within the training paradiagm	Generalised improvements at trained task	Transfer to other tasks
Silver and Oakes	12–18	ASD/AS	11		(✓) NB similar to training set	
Swettenham	6–8	ASD	None (8 TD, 8 Down's also did training)	✓	×	
Tanaka et al.	10.5	ASD, AD PDD-NOS	37 (just did pre- and post-test)	✓	× Only parts/whole identity	
Tartaro and Cassell	7–11	ASD	Within-subjects design	✓ Turn-taking increased during the course of interaction with the virtual peer, not during the interaction with the real peer		
Whalen et al.	3–6	'severe ASD'	22 (teaching as usual)	✓ 15 of the 22 mastered lessons within the training program	(✓) Younger students improved on some but not other standardised vocabulary measures; older children did not	× No improvements on general scale, although a correlation was noted between time spent on training and improvement on general scores

Table 1. (Continued)

Authors	Title	Year	Specific target	Description of training	Training period	Pre- and post-tests	*N*–trained subjects
Schlosser and Blischak	Effects of speech and print feedback on spelling by children with autism	2004	Spelling	Word learning using synthetic speech output and orthographic feedback	Do not report	Retention of taught words	4
Silver and Oakes	Evaluation of a new computer intervention to teach people with autism or Asperger syndrome to recognize and predict emotions in others	2001	Emotion recognition	Pictures of faces and objects, text descriptions of situations	10 30-min sessions over 2 weeks	Facial expression photographs, cartoons depicting emotion-laden situations and non-literal stories	11
Swettenham	Can children with autism be taught to understand false belief using computers?	1996	False belief	Animated computer games presenting a version of the Sally-Anne false belief task	Two sessions (do not say how long) per day for 4 days	Other false belief computer games; Sally-Anne task using dolls; other games testing performance on false belief tasks	8
Tanaka et al.	Using computerized games to teach face recognition skills to children with autism spectrum disorder: the Let's Face It! program	2010	Face recognition	Interactive computer games targeting face recognition skills played at home	20 h (standard deviation = 10.3 h) (≥100 min per week)	Face recognition and emotion recognition from faces	42
Tartaro and Cassell	Playing with virtual peers: bootstrapping contingent discourse in children with autism	2008	Imitation and turn-taking	Interactive games with a virtual peer	Single session	Video-coding of turn-taking with the virtual peer	6
Whalen et al.	Efficacy of TeachTown: basics computer-assisted intervention for the Intensive Comprehensive Autism Program in Los Angeles Unified School District	2010	Vocabulary and other curriculum elements	Computer lessons using a discrete trial format, correct responses trigger animated reward sequences	20 min per day for 3 months	Standardised vocabulary tests; ASD and general behavioural rating scales	22

VR: virtual reality; ASD: autism spectrum disorder; TD: typically developing; HFA: high-functioning autism; AS: Asperger syndrome; LFA: low-functioning autism; PDD-NOS: pervasive developmental disorder–not otherwise specified.

All of the studies included in this review involve some form of evaluation along the lines described above. In Table 1, we document a number of parameters of these evaluations, such as the number of individuals participating and the design used for the control group. We have also evaluated the techniques used for measuring performance improvements as a result of the training, in order to assess the degree to which training improvements translated to improved performance in more ecologically plausible settings, that is, outside of the lab environment. In Table 1, we have divided these evaluations into three categories:

- Were improvements observed at the task being trained over time? 'Within-task' improvements can be assessed only in the trained group.
- Were improvements observed at non-trained tasks that were similar to the task being trained? For example, if the intervention trained emotion recognition, was improved emotion recognition also observed for faces that were not part of the training battery?
- Were improvements observed on tasks that were substantially different to those included in the training battery? For example, if the intervention was intended to improve emotion recognition, were improvements also observed for other aspects of social cognition, such as language or spontaneous social attention?

Overview of article structure

This review is organised into two sections. The section 'Different technologies used to provide cognitive training' discusses the different technologies used to provide the cognitive training interventions evaluated in this review. The interventions that meet our criteria can be divided into four groups: 'Point-and-click software', 'Virtual reality', 'Gaze-contingent interfaces' and 'Robotics'.

The section 'Evaluation' evaluates evidence of the efficacy of these interventions. Our discussion is structured according to three predominant training foci: 'Emotion and face recognition tutors', 'Language and literacy tutors' and 'Social skills tutors'. In relation to each focus, we compare different interventions and evaluate evidence of their relative efficacy.

Different technologies used to provide cognitive training

Point-and-click software

The most readily available approach for providing behavioural interventions in ASD is through CD- or Internet-delivered software applications (e.g. Golan and Baron-Cohen, 2006; Grynszpan et al., 2008; Tanaka et al., 2010). Most of these applications operate via desktop and laptop computers, although we also include touch-screen devices such as iPads that are in use in ongoing research (e.g. Fletcher-Watson et al., 2013). Once developed, these software packages can be distributed electronically at negligible cost, and many can be used by anybody at home. The scalability costs are therefore very low. Software can automatically email records of a user's participation after each session (e.g. Tanaka et al., 2010). This allows clinicians to check each user's compliance and progress, and to adjust the nature of the training set if necessary. Other online features, such as a high-scores website (Tanaka et al., 2010) and online games, can also be used to encourage motivation and participation. These software applications have significant potential scalability. For example, the Fast ForWord program, an auditory perceptual training software package for children with specific language impairment, has been used by over a million students in over 40 countries[7] (Merzenich et al., 1996; Tallal et al., 1996; Temple et al., 2003), although other authors question its effectiveness (Bishop et al., 2006).

One typical example of a behavioural intervention package that uses these methods is the Mind Reading software reported by Golan and Baron-Cohen (2006) (see Figure 1; see also Lacava et al., 2007). A total of 412 emotions are divided into 24 emotion groups and 6 difficulty levels. Each emotion is defined and demonstrated using silent films of faces, voice recordings and written examples of situations that evoke this emotion. The user has the choice either to browse through the emotion library using a traditional point-and-click computer interface, to take structured lessons, or to play one of five different educational games.

Virtual reality

Behavioural intervention packages for ASD such as Treatment and Education of Autistic and related Communication Handicapped Children (TEACCH) (Mesibov and Shea, 2010) and applied behaviour analysis (ABA) (Howard et al., 2005) place a heavy emphasis on structure and repetition, and on establishing a background environment that children do not find overwhelming. Virtual reality (VR) offers the potential for presenting learning tasks that are realistic, but that are presented within a simplified environment. VR environments range from three-dimensional (3D) environments that use a joystick and a home computer (e.g. Mitchell et al., 2007) through to fully immersive environments with a headset display, body tracker and 3D hand controls. Large-scale commercial development by computer game developers has recently seen the cost of these items plummet, with headset-mounted displays and motion sensors available for only several hundred dollars per unit.[8]

Figure 1. A screenshot of the training software presented in Golan et al., 2006.

VR has been used to provide training for specific situations for individuals with ASD (see Parsons and Cobb, 2011, for a recent review). One example of this is the work of Mitchell et al. (2007; see also Parsons, 2005; Parsons et al., 2000, 2004) who used virtual environments (3D computer representations of real environments, which users could manipulate their way around with a joystick) to train subjects in choosing a place to sit in a crowded canteen. VR environments have also been used to train other practical skills such as crossing the road (Josman et al., 2008; Strickland et al., 2007)). Another example comes from Tartaro and Cassell (2008), who presented six high-functioning ASD children aged 7–11 years with a virtual peer (i.e. a computer-animated virtual child, displayed life-size on a screen). This virtual peer was controlled using a 'Wizard of Oz' interface, that is, a human operator hid behind a screen and controlled how the virtual peer reacted. Note that although the operator can be a technician rather than a fully trained clinician, this inclusion of a human operator nevertheless substantially increases the scalability costs of the intervention. VR has also been incorporated with other technologies, for example, to enable gaze-contingent interaction between a system and the user (Grynszpan et al., 2008; see section 'Language and literacy tutors').

Gaze-contingent interfaces

Research has consistently reported atypical patterns of eye-gaze behaviour in ASD, ranging from very early in development (during infancy; Elsabbagh and Johnson, 2007, 2010; Elsabbagh et al., 2009; Wass et al., under review) through to adulthood (e.g. Senju, 2012). For example, atypical eye-gaze behaviours have been noted, particularly during the viewing of dynamic scenes that relate to social anxiety (Speer et al., 2007; Corden et al., 2008). Instructing individuals with ASD to fixate on the eyes increases activity within the fusiform gyrus, the cortical area specialised in face processing (Hadjikani et al., 2004).

Grynszpan et al. (2012; see also Trepagnier et al., 2005, 2006) investigated the effect of gaze-contingent manipulations on eye-gaze behaviour during presentations of scenes in which virtual animated characters spoke sentences that were ambiguous (i.e. interpretable in two ways), and in which the context was provided by the character's facial expressions that enabled disambiguating the sentence and resolving the ambiguity. During the presentation of social scenes in which ambiguous sentences were spoken, they investigated the effect of blurring the screen except for the area around the

Figure 2. Photos of the training phase from Billard et al., 2007.

point where the participant was looking. They did this in order to increase participants' awareness of whether they were looking at the face of the character who was talking. They identified altered eye movement behaviour in the TD group, with smaller changes in the high-functioning autism (HFA) group. No effects of the gaze-contingent manipulation on the comprehensibility of ambiguous sentences were reported; however, the manipulation was only presented for a very short period of time (20 trials).

In comparison to implementations that use traditional point-and-click interfaces, gaze-contingency additionally offers the opportunity for more immersive training environments that are also suitable for the very young and the severely impaired. For example, Wass et al. (2011) used a commercially available eyetracker to develop a battery of training paradigms intended to improve attentional control during infancy. This work offers the future potential for a range of early interventions aimed at infants at high risk of developing ASD as well as other conditions, targeted at early stages of development when brain plasticity is highest (Wass et al., 2012).

Although gaze-contingent applications are currently mainly lab-based, new, low-cost eyetrackers are currently coming onto the market at a cost of approximately US$500 that will open up these applications for home use.[9]

Robotics

The use of 'robot friends' for children with ASD dates back to 1976 (Weir and Emanuel, 1976). Interaction with robots tends to be predictable and repetitive, which are the sorts of interactions that some individuals with ASD prefer (Thakkar et al., 2008). The early studies that have been conducted in this field tend to take the form of imitation interactions, that is, robots that copy the movements of their 'human friend', and this line of research is still thriving (see, for example, Breazeal et al., 2005). This form of interaction is intended as a stepping stone to turn-taking and to other aspects of human-to-human interaction. In robotics, the costs vary considerably depending on the complexity of the application. Of the robots used in the interventions described here, one (from Billard et al., 2007) is commercially available at a cost of US$3000 per unit.[10]

Several examples of the use of robotics come from the AuRoRA project[11] (Dautenhahn, 2000). One version of this project used a robot with a rectangular body and four wheels, exploiting the preference of many children with ASD for mechanical objects. More recent versions (Billard et al., 2007; see Figure 2) feature Robota, a humanoid doll that uses infrared signals to mirror human body movements, is able to learn simple motor sequences, and has bidirectional communication capability (i.e. can invite imitation and imitate herself) (see also Costa et al., 2013 for more recent work from this group). Other examples of robots for ASD include Keepon (Kozima et al., 2007) and work from Feil-Seifer and Mataric (2008) and Duquette et al. (2008; see Figure 3).

Evaluation

In this section, we review evidence of the relative efficacy of the different types of technology-enhanced interventions discussed in the section 'Different technologies used to provide cognitive training'. For reasons of space, not all of the articles included in the Table are mentioned in the text. Our discussion is structured by learning target: 'Emotion and face recognition tutors', 'Language and literacy tutors' and 'Social skills tutors', although each of the categories we consider is itself substantially heterogeneous.

Figure 3. The robot used for training in Duquette et al., 2008.

Figure 4. A screenshot from the educational DVD presented in Golan et al., 2009.

Emotion and face recognition tutors

Section summary: Several interventions have provided home-delivered software or DVD packages that use photos, video clips and text descriptions to teach face recognition and the recognition of emotion from faces. The majority have found that subjects improve within the trained environment, but that these improvements do not generalise to performance of the same task in a real-world environment. The reasons for this are discussed. One recent study (Golan et al., 2009) used a DVD-based approach with younger children (aged 4–7 years) and reported strong generalisation in a number of areas.

Differentiating one face from another is a subtle, and highly specialised, perceptual discrimination task (Johnson, 2010; Johnson et al., 2009; Tarr and Gauthier, 2000). Abnormalities in identifying faces and in recognising the emotions contained on faces and in voices have been variously identified not just in autism (Dawson et al., 2005; Kleinman et al., 2001; see also Jemel et al., 2006) but also in schizophrenia (Feinberg et al., 1986), depression (Gur et al., 1992) and various agnosias, including prosopagnosia (Damasio et al., 1982), Down syndrome (Annaz et al., 2009) and even Williams syndrome (Annaz et al., 2009) (see also Pascalis and Bachevalier, 1998).

Being able to 'read' faces and voices and to glean information from them is fundamental to learning during development (Karmiloff-Smith, 1992, 1998). For example, gaze following during infancy (i.e. the tendency to look where other people are looking) has been shown to correlate with subsequent language development (Brooks and Meltzoff, 2005); similar relationships have been observed for other forms of learning (e.g. Nation and Penny, 2008; Reid and Striano, 2005).

The interventions reviewed here mostly take the form of home-deliverable tutoring systems, based on varying combinations of photographic stimuli, movie clips, voice clips and written descriptions of social situations. In several cases these are accompanied by explicit instructions on how to recognise faces and emotions (e.g. Faja et al., 2008).

Several studies in this area have administered evaluation studies that contain control groups and substantial sample sizes (Golan and Baron-Cohen, 2006 − trained $N = 32$; Tanaka et al., 2010 – $N = 42$), and some have also tested how far learning effects generalise to other areas. For example, in their pre- and post-testing battery, Golan and Baron-Cohen (2006) include some of the faces and emotions from the training set, some faces and emotions not in the intervention, and some clips from feature films. In this particular study (experiment 2), the effect of training was administered relative to a control group who undertook a social skills course for a matched amount of time.

Almost every study has found that the performance of participants within the trained environment improves over time. However, it is striking that three controlled studies (Golan and Baron-Cohen, 2006; Faja et al., 2008; Tanaka et al., 2010) have reported that these improvements fail to generalise to face and emotion recognition tasks that use different faces and emotions to those included in the training set (although Faja et al., 2008 and Tanaka et al., 2010 report some relatively minor changes in face processing strategies). In other words, these studies have failed the test of distal generalisation (see, for example, Green et al., 2010).

The one study that *has* reported distal transfer of training effects is by Golan et al. (2009; see Figure 4, see also Baron-Cohen et al., 2007), who developed an animated TV series called The Transporters[12] in which the faces of human actors are morphed onto trains. This specific design was aimed to encourage and motivate children with ASD, who often prefer mechanical objects that move in a repetitive and predictable manner. The design consists of fifteen 5-min episodes each focusing on a different key emotion or mental state. In a small-scale (trained $N = 20$) evaluation of this approach, Golan et al. (2009) reported that 4- to 7-year-old children who had watched at least 3 × 5-min episodes a day for 4 weeks showed improvements in emotion recognition, even using faces and emotions that were not part of the trained set. These results are encouraging; however, one reservation is that the control groups only took part in pre- and post-testing. The trained group, in addition, also received a booklet encouraging parents to spend one-on-one time with their children discussing the emotions contained in each episode; parents were also encouraged to participate in monitoring their child's participation in the intervention. This increased level of parental involvement does not appear to have been replicated in the wait-list control group.

Language and literacy tutors

Section summary: Several studies have presented explicit word- or spelling-tutoring software for children with ASD, featuring virtual characters acting as tutors and providing phonological/orthographic feedback. Technological interventions are well positioned to provide the sorts of frequent repetition that many subjects with ASD often request; they are also suitable for one-on-one tutoring and can be adapted to a range of abilities and learning speeds. However, many of the studies evaluating the effectiveness of these training packages have only a small sample size and are insufficiently controlled to provide the basis for strong conclusions as to their effectiveness.

Language development is one of the core areas of deficiency in ASD (APA, 1994; Happé and Ronald, 2008). However, there is considerable heterogeneity with regard to the exact nature and severity of the language impairments reported (Kjelgaard and Tager-Flusberg, 2001; Rice et al., 2005; Tager-Flusberg and Joseph, 2003).

For a recent review that focuses on language and literacy-based technology interventions for ASD, we recommend Pennington (2010), who includes 15 studies. In Table 1, we include five studies focusing on teaching vocabulary and spelling; other computerised tutors have focused on other areas of language such as grammar and pragmatics (Grynszpan et al., 2008). These have been excluded from the present review, but have been described in detail in Pennington (2010). Word teaching drills are variously accompanied by object animations (Schlosser and Blischak, 2004) and a computer-animated face that speaks words as they are presented (Massaro and Bosseler, 2006). In a small-scale study (trained $N = 7$), Moore and Calvert (2000) found that retention of taught words was better for computer-presented words than for those taught in a behavioural treatment drill. In another small study (trained – $N = 5$), Massaro and Bosseler (2006) found that words presented concurrently with a computer-animated face that spoke the words for the child were retained better than words presented alone on screen. Schlosser and Blischak (2004) looked at whether adding synthetic speech output and orthographic feedback improved the efficacy of their spelling tutor; they found that it did, but they did not perform statistical tests on their small sample (trained $N = 4$).

Hetzroni and Tannous (2004) developed a tutor that focused on the pragmatics of language communication. It was based on structured, turn-based, play that involved participating in recorded sentences reflecting real-world situations and pressing buttons to indicate their responses in everyday situations (such as going to a restaurant). They tested it on five children with ASD that had a tendency towards echolalia – repeating spoken words or parts of words, which is a normal developmental phase, but which is often excessive and maladaptive in ASD (Wing and Gould, 1979). Even after a relatively small amount of time playing the games (18 × 10- to 25-min sessions), video-coding of the children's behaviour in a free play environment demonstrated a reduced tendency towards echolalia. Unfortunately, again, sample sizes are small and no control group was included.

Whalen et al. (2010) administered *TeachTown*, a training system that relies on the principles of ABA to remediate specific learning deficits such as receptive and expressive vocabulary. The software, which took a trial-by-trial format, was presented for 20 minutes per school-day for 3 months to 22 three- to six-year-old children, and the effects were assessed relative to a 'no treatment' control group. Younger children improved on some standardised language assessments post-training, but older children did not show such improvements. No changes were identified on global behavioural rating scales (the Brigance Inventory of Early Development and the Childhood Autism Rating Scale), although relationships were observed on some measures between progress within the training package and progress on global behavioural scales.

Social skills tutors

Section summary: a variety of methods have been used to train social skills in ASD subjects. The tasks vary from false belief tasks to social situations such as choosing where to sit in a crowded canteen. Computer-generated human faces have been used, and virtual environments, as well as more traditional point-and-click software packages, that work either via text descriptions, videos/animations or a combination of media. As with the emotion and face recognition tutors, no study has conclusively shown that within-task improvements can generalise to a real-world environment.

Swettenham (1996) designed animated computer games based on text and drawn pictures of different social

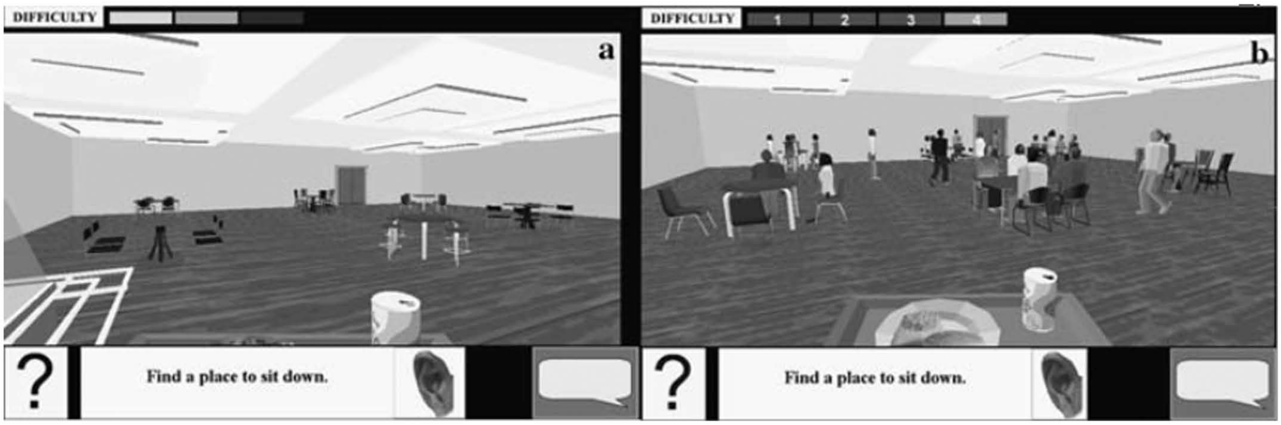

Figure 5. A screenshot from the software presented in Mitchell et al., 2007.

situations aimed to teach children with ASD the Sally-Anne false belief task, which is classically used to assess Theory of Mind, the understanding that others have mental states discrete from their own (Baron-Cohen et al., 1985). Swettenham (1996) measured the performance of children within the trained task, and then, in another thorough experimental design, tested how far the trained improvements had generalised using a graded variety of computerised and real-world false belief tasks. They also found that children with ASD were able to improve within the training paradigm, but that these improvements did not transfer to more real-world assessments.

Mitchell et al. (2007, see Figure 5; see also Parsons, 2005; Parsons et al., 2000, 2004) used VR to train subjects in choosing a place to sit in a crowded canteen. Generalisation of training improvements was assessed by asking individuals with ASD to make decisions based on video recordings of real-life situations and to justify their choices. Several instances of improved judgements as well as improvements in the quality of the social reasons given to justify their choices were identified.

Duquette et al. (2008; see Figure 3) found that exposing two children with 'low-functioning' ASD to structured play with a robot that imitated facial expressions, body movements and familiar actions led to more shared attention and imitation of facial expression with their 'robot friend' than the human-trained children, although other measures such as imitation of body movements were not improved.

Bauminger-Zvieli et al. (2012) report on two programs designed to teach social conversation, based on the principles of Cognitive Behavioural Therapy (CBT). One of these was administered on a tabletop display and the other on a laptop; they were administered over twelve 45-min training sessions to 22 children with ASD. Pre–post measures that showed significant training improvements included performance on experimental assessments of problem-solving, concept clarification and Theory of Mind that had not been part of the training battery; they also reported some improvements in social engagement as coded from observation of a shared drawing task. Although these results are encouraging, the fact that no control group was included in this study means test–retest effects cannot be discounted; furthermore, the large variance in the age of the participants included (mean = 9.8 years, standard deviation = 10.7 years) means that the results reported need to be treated with caution.

Figure 6. A child using the ECHOES software, taken from Bernardini et al. (in press).

Bernardini et al. (2012) report on the development of an autonomous virtual agent that children with autism interact with via a touch-screen interface (the ECHOES project; see Figure 6). A total of 12 different activities are presented using this agent, aimed to encourage turn-taking and joint attention, specifically focusing on children's initiations of bids for interaction and responding to bids for interaction. Pre- and post-testing involving 19 children mirrored the structured turn-taking interaction with a real-life peer. Although the number of social initiations (e.g. bids for joint attention) in a real-life setting did not change pre to post, some within-environment change for a subgroup of children with ASD was observed. The number of initiations to both the virtual agent and human facilitator within ECHOES increased in eight children, with seven unchanged and four showing a decrease. The improvements that were observed reached significance for the social behaviours using (a) gaze for social referencing (the child looks towards a partner for information) and (b) social sharing (the child initiates joint attention through a combination of gaze and gesture to convey enjoyment and interest) and for children's speech to the agent (see also Rajendran et al., 2013).

Discussion

> … I hear too much and see too much but my sense organs are ok – it's just that inside it all sets off – words, sentences, ideas get torn apart and jumbled up … (Sellin, 1993)[13]

Of the studies we have reviewed, it is striking that the studies that explicitly tested for distal transfer, that is, the generalisation of training improvements to non-overlapping but similar tasks outside the trained set, have generally reported negative results (Faja et al., 2008; Golan and Baron-Cohen, 2006; Swettenham, 1996; Tanaka et al., 2010). This is in contrast to the results of other studies that are more encouraging, but for which there are reservations about the control groups (such as Bauminger-Zvieli et al., 2012; Golan et al., 2009).

The lack of distal transfer observed in the studies to date may reflect the well-documented problems that many individuals with ASD experience in generalising and extrapolating their experiences (Cohen, 2007; Golan and Baron-Cohen, 2006; Grandin, 2006; Plaisted, 2001). Thus, for example, individuals with ASD might learn to solve a training task that trains at recognising emotions that are presented in a simplified fashion on an avatar face by using particular cues that are present in an Avatar face but absent in a 'real-world' face. Thus, improvements are observed within the computerised training paradigm, but these improvements are not found in 'real-world' environments (Cohen, 2007).

Future work should concentrate on helping individuals with ASD to bridge this gap between computerised and real-world environments, and on understanding what aspects – together and individually – of the virtual environments, including the communication modalities facilitated through them, type of rendering used (e.g. photorealistic vs cartoonish, two-dimensional (2D) or 3D), their adaptability and adaptivity, the control that the user has over them, and their portability, bring the greatest promise. It may be that some types of knowledge that are procedural and rule-based (such as how to cross a road) can be shown to transfer whereas other types of knowledge (such as what anger is) do not (Parsons and Cobb, 2011).

However, we additionally wish to propose a more subtle way of addressing this issue. Convergent evidence suggests that ASD is not simply a problem of subjects lacking specific pieces of declarative knowledge (e.g. 'not knowing' what emotions are), but rather one of applying what they know in noisy, overwhelming real-world settings (e.g. Doherty-Sneddon et al., 2002; Doherty-Sneddon and Phelps, 2005; Senju, 2012; Speer et al., 2007; see also Grandin, 2006; Sellin, 1993). Similarly, within neuroscience, researchers are increasingly viewing ASD as a condition in which abnormal neural connectivity patterns, possibly accompanied by excitatory/inhibitory neurotransmitter imbalances, lead to a 'noisier' brain – that is, a brain that is less able to filter out signals from noise (Rippon et al., 2007; Rubenstein and Merzenich, 2003; Wass, 2010).

These new approaches suggest that rather than attempting to 'solve' autism by remediating specific pieces of declarative knowledge that are lacking, interventions should instead concentrate on helping individuals to apply knowledge within the context of the world as it feels to them, where self-reports of 'sensory overload' and 'overstimming' are common (e.g. Grandin, 2006; Sellin, 1993). Technology offers countless possibilities here. The amount of background distraction can be adaptively varied depending on how well the subject is performing the task (cf. Mitchell et al., 2007), in a way that is virtually impossible in a real-world environment. In particular, VR offers the possibility of gradually integrating multimodal information (proprioceptive, visual, auditory and tactile) at a pace that is defined by the user. These may represent fruitful targets for future work. One irony is that the simplified nature of technological environments may be both the reason why individuals with ASD like them (due to their simplified nature, which avoids 'sensory overload') *and* the reason why learning has difficulty transferring to real-world settings. (Similar debates also take place in the design of toddler-directed TV, where simplified cartoon and puppet-like faces are easier to parse (and so preferred by young viewers) but are also less semantically informative than 'real' faces (Wass and Smith, under review)). In the case of VR, however, the development of increasingly complex, photorealistic environments means that it may one day be possible to bridge the gap between simplified, 'virtual' and complex, 'real' environments.

Another area that we believe should be explored in future is that of early interventions. A number of authors have concluded that early, intensive interventions are most likely to be successful because neural and behavioural plasticity is greater earlier in development (Dawson, 2008; Heckman, 2006; Myers et al., 2007; Wass et al., 2012). Many of the most promising technological interventions we have reviewed have targeted young individuals with ASD, although the number of studies in this area is very small (Golan et al., 2009 − 4- to 7-year-olds; Whalen et al., 2010 − 3- to 6-year-olds). We have also discussed work from Wass et al. (2011) who administered gaze-contingent attentional control training to 42 TD 11-month-old infants and found in an active-controlled, medium-scale trial that 75 minutes of training over four training sessions led to immediate improvements in a number of different aspects of attentional control. Interventions targeting infants at elevated risk of developing ASD and young toddlers with early diagnosed ASD should be a focus of future work, taking advantage of the potentials offered by robotics and gaze-contingent environments.

We have pointed out that many of the studies included in this review have lacked adequate control groups and blinding procedures. Well-designed intervention trials (with a randomised, matched clinical control group including either current best practice treatment groups or technology placebos (Kaptchuk et al., 2000), adequate sample sizes and a large enough training period) are expensive and time consuming to run, but are vitally useful in assessing the utility of interventions. This allows for the long-term refinement and development of training targets.

Finally, in attempting to facilitate the transfer of skills between the virtual and the real worlds, it is wise to consider the exact context within which the given technology may be placed, specifically the role that other persons (practitioners, parents, peers) may play in the intervention process. The importance of considering not only the exact intervention that a technology might deliver, but also the wider context in which it might be used, has been highlighted by many researchers in the area of the Learning Sciences (e.g. Sawyer, 2006) in relation to educational technologies in general. Just as a book may not be used in isolation from the remaining learning experiences of a pupil, a piece of technology will involve different forms of interaction with others, which may influence the success of an intervention (both the process by which the intervention is delivered and its possible outcomes) – an issue that emerged during the ECHOES technology-enhanced autism intervention project (e.g. Bernardini et al., 2012; Porayska-Pomsta et al., 2012), and which also constitutes the focus of the Shape project[14] (Guldberg et al., 2013). Shape investigates how teachers and children use different, independently evaluated technology-enhanced approaches to promote social interaction without interference or instructions from researchers. The potential impact of others' involvement in a technology-enhanced intervention on distal transfer is also highlighted through the Golan et al. (2009) study, where children's parents were encouraged actively to participate in the intervention by discussing the content of the activities with their children.

In concluding this review, we have noted a number of challenges in this area, as well as exciting avenues for the future. In particular we emphasised three points that we believe should be a focus for future work: (a) a shift of emphasis, away from *teaching children with ASD what they do not know* and towards *helping children with ASD to apply their knowledge in complex, real-world environments*, (b) an emphasis on intensive interventions targeted at early stages of development when neural and behavioural plasticity is highest and (c) the wider adoption of rigorous, properly powered and controlled experimental designs for assessing an intervention's effectiveness.

Acknowledgements

The authors thank Thusha Rajendran and Emily Jones for reading drafts of this article.

Funding

This work was supported by a Bloomsbury Consortium studentship, by Medical Research Council (UK) Programme Grant G0701484 to Professor Mark Johnson, by TLRP/EPSRC grant number RES-139-25-0395 and by a British Academy Postdoctoral Fellowship.

Notes

1. ich staune wessen geduld aber grosser ist deine oder die von einem computer die vom computer ist doch unaufrichtig ganz fast ehrlich dagegen die von dir tatsache ist ich konnte mit fast fuenf jahren auch schon schreiben und sogar rechnen aber es hat niemand gemerkt weil ich so chaotisch war aber das war ich einfach aus angst vor den menschen gerade weil ich unfaehig war zu reden fiel mir das lesen so leicht. (translation by S Wass)
2. http://slurl.com/secondlife/Porcupine/37/185/105/
3. http://www.autismandcomputing.org.uk/
4. http://www.autistics.org/
5. http://www.youtube.com/watch?v=JnylM1hI2jc
6. www.scilearn.com
7. https://fastforward.co./au/programs/faqs-2/
8. http://www.stereo3d.com/hmd.htm#chart
9. http://www.tobii.com/rexvip
10. www.didel.com
11. www.aurora-project.com
12. www.thetransporters.com
13. … ich kann ein wenig zu viel hoeren and zu viel sehen aber die sinnesorgane sind o.k. einfach innen geht ein durcheinander leider los woerter saetze ideen werden so auseinandergerissen und zerissen die einfachsten dinge werden aus dem zusammenhang der wichtigen wirklichen einzelnen anderen aussenwelt gerissen … (translation by S Wass)
14. http://www.birmingham.ac.uk/research/activity/education/shape/index.aspx

References

American Psychiatric Association (APA) (1994) *Diagnostic and Statistical Manual of Mental Disorders* (DSM-IV). 4th ed. Washington, DC: APA.

Annaz D, Karmiloff-Smith A, Johnson MH, et al. (2009) A cross-syndrome study of the development of holistic face recognition in children with autism, Down syndrome, and Williams syndrome. *Journal of Experimental Child Psychology* 102(4): 456–486.

Arroyo I and Woolf BP (2005) Inferring learning and attitudes from a Bayesian network of log file data. In: *Proceedings of the 2005 conference on artificial intelligence in education:*

Supporting learning through intelligent and socially informed technology. Amsterdam, IOS Press, 2005.
Baron-Cohen S (2002) The extreme male brain theory of autism. *Trends in Cognitive Sciences* 6(6): 248–254.
Baron-Cohen S, Golan O, Chapman E, et al. (2007) Transported to a world of emotion. *Psychologist* 20(2): 76–77.
Baron-Cohen S, Leslie AM and Frith U (1985) Does the autistic child have a 'theory of mind'? *Cognition* 21(1): 37–46.
Bauminger-Zviely N, Eden S, Zancanaro M, Weiss PL, Gal E (2012) Increasing social engagement in children with high-functioning autism spectrum disorder using collaborative technologies in the school environment. *Autism* 17(3): 317–39.
Beauregard M (2007) Mind does really matter: evidence from neuroimaging studies of emotional self-regulation, psychotherapy, and placebo effect. *Progress in Neurobiology* 81(4): 218–236.
Bernard-Opitz V, Sriram N and Nakhoda-Sapuan S (2001) Enhancing social problem solving in children with autism and normal children through computer-assisted instruction. *Journal of Autism and Developmental Disorders* 31(4).
Bernardini S, Porayska-Pomsta K, Smith T, et al. (in press) Virtual social partners for children with autism. *Information Sciences, Special Issue of Serious Games*. Elsevier.
Bernardini S, Porayska-Pomsta K, Smith T, et al. (2012) Building autonomous agents for children with ASD. In: *12th international conference on intelligent virtual agents*, Santa Cruz, CA, 12–14 September.
Billard A, Robins B, Nadel J, et al. (2007) Building Robota, a mini-humanoid robot for the rehabilitation of children with autism. *Assistive Technology* 19(1): 37–49.
Bishop DVM, Adams CV and Rosen S (2006) Resistance of grammatical impairment to computerised comprehension training in children with specific and non-specific language impairments. *International Journal of Language & Communication Disorders* 41(1): 19–40.
Bishop J (2003) The Internet for educating individuals with social impairments. *Journal of Computer Assisted Learning* 19(4): 546–556.
Bölte S, Feineis-Matthews S. Leber S, Dierks T, Hubl D and Poustka F (2002) The development and evaluation of a computer-based program to rest and to teach the recognition of facial affect. *International Journal of Circumpolar Health* 61(Suppl.2): 61–68.
Breazeal C, Buchsbaum D, Gray J, et al. (2005) Learning from and about others: towards using imitation to bootstrap the social understanding of others by robots. *Artificial Life* 11(1–2): 31–62.
Brooks R and Meltzoff AN (2005) The development of gaze following and its relation to language. *Developmental Science* 8(6): 535–543.
Cohen IL (2007) A neural network model of autism. Implications for theory and treatment. In: Mareschal D, Sirois S, Westermann G and et al. (eds) *Neuroconstructivism: Perspectives and Prospects*, vol. II. Oxford University Press, Oxford, UK.
Costa S, Lehmann H, Robins B, Dautenhahn K and Soares F (2013) "Where is your nose?" – Developing body awareness skills among Children with Autism using a humanoid robot, In: *Proceedings of ACHI 2013, The sixth international conference on advances in computer-human interactions*, 24 February–1 March 2013, Nice, France, 117–122.
Cramer MD, Hirano S, Tentori M, et al. (2011) Classroom-based assistive technology: collective use of interactive visual schedules by students with autism. In: *CHI'11*, Vancouver, BC, Canada, 7–12 May.
Damasio AR, Damasio H and Van Hoesen GW (1982) Prosopagnosia: anatomic basis and behavioural mechanisms. *Neurology* 32(4): 331–341.
Dautenhahn K (2000) Making friends with robots: an artificial life perspective on socially intelligent agents. *International Journal of Psychology* 35(3–4): 204.
Dawson G (2008) Early behavioural intervention, brain plasticity, and the prevention of autism spectrum disorder. *Development and Psychopathology* 20(3): 775–803.
Dawson G and Watling R (2000) Interventions to facilitate auditory, visual, and motor integration in autism: A review of the evidence. *Journal of Autism and Developmental disorders* 30: 415–421.
Dawson G, Webb SJ and McPartland J (2005) Understanding the nature of face processing impairment in autism: insights from behavioural and electrophysiological studies. *Developmental Neuropsychology* 27(3): 403–424.
Di Gennaro Reed FD, Hyman SR and Hirst JM (2011) Applications of technology to teach social skills to children with autism. *Research in Autism Spectrum Disorders* 5: 1003–1010.
Doherty-Sneddon G and Phelps F (2005) Gaze aversion: a solution to cognitive or social difficulty? *Memory and Cognition* 33: 727–733.
Doherty-Sneddon G, Bruce V, Bonner L, et al. (2002) Development of gaze aversion as disengagement from visual information. *Developmental Psychology*, 38: 438–445.
Du Boulay D (in press) Motivationally intelligent educational systems: the contribution of the human centred technology research group. *Technology, Instruction, Cognition and Learning*.
Duquette A, Michaud F and Mercier H (2008) Exploring the use of a mobile robot as an imitation agent with children with low-functioning autism. *Autonomous Robots* 24(2): 147–157.
Dweck CS (1986) Motivational processes affecting learning. *American Psychologist* 41(10): 1040–1048.
El Kaliouby R and Robinson P (2004) Emotional hearing aid: an assistive tool for children with Asperger's syndrome. In: Keates S and Clarkson J (eds) *Designing a More Inclusive World*. London: Springer, pp. 163–172.
El Kaliouby R, Picard R and Baron-Cohen S (2006) Affective computing and autism. *Progress in Convergence: Technologies for Human Wellbeing* 1093: 228–248.
Elsabbagh M and Johnson MH (2007) Infancy and autism: progress, prospects, and challenges. *Progress in Brain Research* 164: 355–383.
Elsabbagh M and Johnson MH (2010) Getting answers from babies about autism. *Trends in Cognitive Sciences* 14(2): 81–87.
Elsabbagh M, Volein A, Holmboe K, et al. (2009) Visual orienting in the early broader autism phenotype: disengagement and facilitation. *Journal of Child Psychology and Psychiatry* 50(5): 637–642.
Escobedo L, Nguyen DH, Boyd LA, et al. (2012) MOSOCO: a mobile assistive tool to support children with autism practicing social skills in real-life situations. In: *Proceeding CHI '12*, Chi, Austin, Texas, May 2012.
Faja S, Aylward E, Bernier R, et al. (2008) Becoming a face expert: a computerised face-training program for high-functioning individuals with autism spectrum disorders. *Developmental Neuropsychology* 33(1): 1–24.
Feil-Seifer D and Mataric MJ (2008) A control architecture for autonomous robot-assisted behavior intervention for children with Autism Spectrum Disorders. In: *17th IEEE international*

symposium on robot and human interactive communication, vols 1 and 2, Munich, Germany, 1–3 August, pp. 328–333. IEEE.

Feinberg TE, Rifkin A, Schaffer C, et al. (1986) Facial discrimination and emotional recognition in schizophrenia and affective disorders. *Archives of General Psychiatry* 43(3): 276–279.

Fletcher-Watson S, Hammond S, O'Hare A, et al. (2013) Click-east: evaluating the impact of an ipad app on social communicative abilities in young children with autism. In: IMFAR, San Sebastian, Spain, 4 May.

Foundation for People with Learning Disabilities (2007) *The Economic Consequences of Autism in the UK*.

Golan O and Baron-Cohen S (2006) Systemizing empathy: teaching adults with Asperger syndrome or high-functioning autism to recognize complex emotions using interactive multimedia. *Development and Psychopathology* 18(2): 591–617.

Golan O, Ashwin E, Granader Y, et al. (2009) Enhancing emotion recognition in children with autism spectrum conditions: an intervention using animated vehicles with real emotional faces. *Journal of Autism and Developmental Disorders* 40(3): 269–279.

Grandin T (2006) *Thinking in Pictures*. 2nd ed. London: Bloomsbury.

Green J and Dunn G (2008) Using intervention trials in developmental psychiatry to illuminate basic science. *British Journal of Psychiatry* 192(5): 323–325.

Green J, Charman T, McConachie H, et al. (2010) Parent-mediated communication-focused treatment in children with autism (PACT): a randomised controlled trial. *Lancet* 375(9732): 2152–2160.

Grynszpan O, Martin JC and Nadelc J (2008) Multimedia interfaces for users with high functioning autism: an empirical investigation. *International Journal of Human-Computer Studies* 66(8): 628–639.

Grynszpan O, Nadel J, Martin J-C, et al. (2012) Self-monitoring of gaze in high functioning autism. *Journal of Autism and Developmental Disorders* 42: 1642–1650.

Guldberg K, Kossyvaki L, Keay-Bright W, et al. (2013) The future use of technologies in the classroom: participatory research and E-inclusion as tools to promote creativity at schools. In: *The European conference on educational research*, Istanbul, September 2013.

Gur RC, Erwin RJ, Gur RE, et al. (1992) Facial emotion discrimination: II. Behavioural findings in depression. *Psychiatry Research* 42(3): 241–251.

Happé F and Ronald A (2008) The 'Fractionable Autism Triad': a review of evidence from behavioural, genetic, cognitive and neural research. *Neuropsychology Review* 18(4): 287–304.

Heckman JJ (2006) Skill formation and the economics of investing in disadvantaged children. *Science* 312(5782): 1900–1902.

Herrera G, Alcantud F, Jordan R, et al. (2008) Development of symbolic play through the use of virtual reality tools in children with autistic spectrum disorders. *Autism* 12(2): 143–157.

Hetzroni OE and Tannous J (2004) Effects of a computer-based intervention program on the communicative functions of children with autism. *Journal of Autism and Developmental Disorders* 34(2): 95–113.

Holsbrink-Engels GA (2001) Using a computer learning environment for initial training in dealing with social-communicative problems. *British Journal of Educational Technology* 32(1): 53–67.

Howard JS, Sparkman CR, Cohen HG, et al. (2005) A comparison of intensive behavior analytic and eclectic treatments for young children with autism. *Research in Developmental Disabilities* 26(4): 359–383.

Jemel B, Mottron L and Dawson M (2006) Impaired face processing in autism: fact or artifact? *Journal of Autism and Developmental Disorders* 36(1): 91–106.

Johnson MH (2010) *Developmental Cognitive Neuroscience*. 3rd ed. Hoboken, NJ: Wiley-Blackwell.

Johnson MH, Grossmann T and Kadosh KC (2009) Mapping functional brain development: building a social brain through interactive specialization. *Developmental Psychology* 45(1): 151–159.

Josman N, Ben-Chaim MH, Friedrich S, et al. (2008) Effectiveness of virtual reality for teaching street-crossing skills to children and adolescents with autism. *International Journal on Disability and Human Development* 7: 49–56.

Jung K-E, Lee H-J, Lee Y-S, et al. (2006) The application of a sensory integration treatment based on virtual reality-tangible interaction for children with Autistic Spectrum Disorder. *PsychNology* 4(2): 145–159.

Kaptchuk TJ, Goldman P, Stone DA, et al. (2000) Do medical devices have enhanced placebo effects? *Journal of Clinical Epidemiology* 53: 786–792.

Karmiloff-Smith A (1992) *Beyond Modularity: A Developmental Perspective on Cognitive Science*. MIT Press, Cambridge, MA.

Karmiloff-Smith A (1998) Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences* 2(10): 389–398.

Keay-Bright W (2006) ReActivities (c): autism and play. *Digital Creativity* 17(3): 149–156.

Kientz JA (2012) Embedded capture and access: encouraging recording and reviewing of data in the caregiving domain. *Personal and Ubiquitous Computing* 16(2): 209–221.

Kientz JA, Arriaga RI and Abowd GD (2009) Baby steps: evaluation of a system to support record-keeping for parents of young children. In: Proceedings of the 2009 conference on human factors in computing systems – CHI 2009, Austin, TX, 5–10 May.

Kientz JA, Hayes GR, Westeyn T, et al. (2007) Pervasive computing and autism: assisting caregivers of children with special needs. *IEEE Pervasive Computing* 6(1): 28–35.

Kjelgaard MM and Tager-Flusberg H (2001) An investigation of language impairment in autism: implications for genetic subgroups. *Language and Cognitive Processes* 16(2–3): 287–308.

Kleinman J, Marciano PL and Ault RL (2001) Advanced theory of mind in high-functioning adults with autism. *Journal of Autism and Developmental Disorders* 31: 29–36.

Kouijzer MEJ, de Moor JMH, Gerrits BJL, et al. (2009) Neurofeedback improves executive functioning in children with autism spectrum disorders. *Research in Autism Spectrum Disorders* 3(1): 145–162.

Kozima H, Yasuda Y and Nakagawa C (2007) *Social* interaction facilitated by a minimally-designed robot: Findings from longitudinal therapeutic practices for autistic children. In: *2007 RO-MAN: 16th IEEE international symposium on robot and human interactive communication*, vols 1–3, Jeju, 26–29 August, pp. 598–603. IEEE, Jeju, South Korea.

Lacava PG, Golan O, Baron-Cohen S, et al. (2007) Using assistive technology to teach emotion recognition to students with

Asperger syndrome: a pilot study. *Remedial and Special Education* 28(3): 174–181.
Massaro DW and Bosseler A (2006) Read my lips: the importance of the face in a computer-animated tutor for vocabulary learning by children with autism. *Autism* 10(5): 495–510.
Merzenich MM, Jenkins WM, Johnston P, et al. (1996) Temporal processing deficits of language-learning impaired children ameliorated by training. *Science* 271(5245): 77–81.
Mesibov GB and Shea V (2010) The TEACCH program in the era of evidence-based practice. *Journal of Autism and Developmental Disorders* 40(5): 570–579.
Mitchell P, Parsons S and Leonard A (2007) Using virtual environments for teaching social understanding to 6 adolescents with autistic spectrum disorders. *Journal of Autism and Developmental Disorders* 37(3): 589–600.
Moore D, Cheng Y, McGrath P and Norman J (2005) Collaborative virtual environment technology for people with autism. *Focus on Autism and Other Developmental* 20(4): 231–243.
Moore M and Calvert S (2000) Brief report: vocabulary acquisition for children with autism: teacher or computer instruction. *Journal of Autism and Developmental Disorders* 30(4): 359–362.
Murray D, Lesser M and Lawson W (2005) Attention, monotropism and the diagnostic criteria for autism. *Autism* 9(2): 139–156.
Myers SM, Johnson CP and the Council on Children with Disabilities (2007) Management of children with autism spectrum disorders. *Pediatrics* 120(5): 1162–1182.
Nation K and Penny S (2008) Sensitivity to eye gaze in autism: is it normal? Is it automatic? Is it social? *Development and Psychopathology* 20(1): 79–97.
Parsons S (2005) Use, understanding and learning in virtual environments by adolescents with autistic spectrum disorders. *Annual Review of CyberTherapy and Telemedicine* 3: 207–215.
Parsons S and Cobb S (2011) State-of-the-art of Virtual Reality technologies for children on the autism spectrum. *European Journal of Special Needs Education* 26(3): 355–366.
Parsons S, Beardon L, Neale HR, et al. (2000) Development of social skills amongst adults with Asperger's syndrome using virtual environments: the AS interactive project. In: *3rd International Conference on Disability, Virtual Reality and Associated Technologies*, Sardinia, Italy, 23–25 September, Alghero, Sardinia, Italy http://www.icdvrat.reading.ac.uk/2000/index2000.htm pp. 163–170
Parsons S, Mitchell P and Leonard A (2004) The use and understanding of virtual environments by adolescents with autistic spectrum disorders. *Journal of Autism and Developmental Disorders* 34: 449–466.
Pascalis O and Bachevalier J (1998) Face recognition in primates: a cross-species study. *Behavioural Processes* 43(1): 87–96.
Pennington RC (2010) Computer-assisted instruction for teaching academic skills to students with autism spectrum disorders: a review of literature. *Focus on Autism and Other Developmental Disabilities* 25(4): 239–248.
Picard RW (1997) *Affective Computing*. Boston, MA: MIT Press.
Picard RW (2009) Future affective technology for autism and emotion communication. *Philosophical Transactions of the Royal Society B-Biological Sciences* 364(1535): 3575–3584.
Picard RW, Papert S, Bender W, et al. (2004) Affective learning – a manifesto. *Bt Technology Journal* 22(4): 253–269.
Piper AM, O'Brien E, Morris MR, et al. (2006) SIDES: a cooperative tabletop computer game for social skills development. In: *Proceedings of Computer Supported Cooperative Work CSCW*, 4-8 November 2006, Banff, Alberta, Canada. New York: ACM Press, pp. 1–10.
Plaisted KC. (2001) Reduced generalization in autism: an alternative to weak central coherence. In: Burack JA, Charman T, Yirmiya N, et al. (eds) *The Development of Autism: Perspectives from Theory and Research*. Mahwah, NJ: Lawrence Erlbaum Associates, pp. 149–172.
Porayska-Pomsta K, Frauenberger C, Pain H, et al. (2012) Developing technology for autism: an interdisciplinary approach. *Personal and Ubiquitous Computing* 16(2): 117–127.
Rajendran G and Mitchell P (2000) Computer mediated interaction in Asperger's syndrome: the Bubble Dialogue program. *Computers & Education* 35(3): 189–207.
Rajendran T, Porayska-Pomsta K, Smith T, and the ECHOES consortium (2013) The Echoes technology-enhanced learning environment: facilitating social communication skills in children with autism. In: *IMFAR*, Glasgow, UK, 5–7 September.
Reid VM and Striano T (2005) Adult gaze influences infant attention and object processing: implications for cognitive neuroscience. *European Journal of Neuroscience* 21(6): 1763–1766.
Rice ML, Warren SF and Betz SK (2005) Language symptoms of developmental language disorders: an overview of autism, Down syndrome, fragile X, specific language impairment, and Williams syndrome. *Applied Psycholinguistics* 26(1): 7–27.
Rippon G, Brock J, Brown C, et al. (2007) Disordered connectivity in the autistic brain: challenges for the 'new psychophysiology'. *International Journal of Psychophysiology* 63(2): 164–172.
Rubenstein JLR and Merzenich MM (2003) Model of autism: increased ratio of excitation/inhibition in key neural systems. *Genes, Brain and Behavior* 2(5): 255–267.
Sansosti FJ and Powell-Smith KA (2008) Using computer-presented social stories and video models to increase the social communication skills of children with high-functioning autism spectrum disorders. *Journal of Positive Behavior Interventions* 10(3): 162–178.
Sawyer K (2006) *The Cambridge Handbook of the Learning Sciences*. Cambridge University Press, Cambridge, UK.
Schlosser RW and Blischak DM (2004) Effects of speech and print feedback on spelling by children with autism. *Journal of Speech Language and Hearing Research* 47(4): 848–862.
Sellin B (1993) *Ich will kein inmich mehr sein – botschaften aus einem autistischen kerker*. Buechergilde Gutenberg, Frankfurt, Germany.
Senju A (2012) Atypical development of spontaneous social cognition in autism spectrum disorders. *Brain & development* 35(2): 96–101.
Silver M and Oakes P (2001) Evaluation of a new computer intervention to teach people with autism or asperger syndrome to recognize and predict emotions in others. *Autism* 5(3): 299–316.
Speer LL, Cook AE, McMahon WM, et al. (2007) Face processing in children with autism: effects of stimulus contents and type. *Autism* 11(3): 265–277.
Strickland DC, McAllister D, Coles CD, et al. (2007) An evolution of virtual reality training designs for children with autism and fetal alcohol spectrum disorders. *Topics in Language Disorders* 27(3): 226–241.

Swettenham J (1996) Can children with autism be taught to understand false belief using computers? *Journal of Child Psychology and Psychiatry and Allied Disciplines* 37(2): 157–165.

Tager-Flusberg H and Joseph RM (2003) Identifying neurocognitive phenotypes in autism. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* 358(1430): 303–314.

Tallal P, Miller SL, Bedi G, et al. (1996) Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science* 271(5245): 81–84.

Tanaka JW, Wolf JM, Klaiman C, et al. (2010) Using computerised games to teach face recognition skills to children with autism spectrum disorder: the Let's Face It! program. *Journal of Child Psychology and Psychiatry* 51(8): 944–952.

Tarr MJ and Gauthier I (2000) FFA: a flexible fusiform area for subordinate-level visual processing automatised by expertise. *Nature Neuroscience* 3(8): 764–769.

Tartaro A and Cassell J (2008) Playing with virtual peers: bootstrapping contingent discourse in children with autism. In: Proceedings of international conference of the learning sciences (ICLS), Utrecht, The Netherlands, 24–28 June, pp. 382–389. Utrecht: ACM Press.

Temple E, Deutsch GK, Poldrack RA, et al. (2003) Neural deficits in children with dyslexia ameliorated by behavioural remediation: evidence from functional MRI. *Proceedings of the National Academy of Sciences of the United States of America*. 100(5): 2860–2865.

Thakkar KN, Polli FE, Joseph RM, et al. (2008) Response monitoring, repetitive behaviour and anterior cingulate abnormalities in autism spectrum disorders (ASD). *Brain* 131: 2464–2478.

Trepagnier CY, Sebrechts MM and Finkelmeyer A (2005) Simulating social interaction to address deficits of autistic spectrum disorder in children. In: 4th International Workshop on Virtual Rehabilitation (IWVR2005), Catalina Island, CA, 19–21 September.

Trepagnier CY, Sebrechts MM, Finkelmeyer A, et al. (2006) Acceptance of a virtual social environment by pre-schoolers with autism spectrum disorder. *Cyberpsychology & Behavior* 9(6): 723.

Wainer AL and Ingersoll BR (2011) The use of innovative computer technology for teaching social communication to individuals with autism spectrum disorders. *Research in Autism Spectrum Disorders* 5(1): 96–107.

Wass SV (2010) Distortions and disconnections: disrupted brain connectivity in autism. *Brain and Cognition* 75(1): 18–28.

Wass SV, Porayska-Pomsta K and Johnson MH (2011) Training attentional control in infancy. *Current Biology* 21: 1543–1547.

Wass SV, Scerif G and Johnson MH (2012) Training attentional control and working memory: is younger, better? *Developmental Review* 32(4): 360–387.

Weir S and Emanuel R (1976) *Using LOGO to Catalyse Communication in an Autistic Child* (Technical Report DAI Research. Report no. 15). Edinburgh: University of Edinburgh.

Whalen C, Moss D, Ilan AB, et al. (2010) Efficacy of TeachTown: basics computer-assisted intervention for the Intensive Comprehensive Autism Program in Los Angeles Unified School District. *Autism* 14(3): 179–197.

Wilkinson N, Ang RP and Goh DH (2008) Online video game therapy for mental health concerns: a review. *International Journal of Social Psychiatry* 54(4): 370–382.

Wing L and Gould J (1979) Severe impairments of social interaction and associated abnormalities in children: epidemiology and classification. *Journal of Autism and Developmental Disorders* 9(1): 11–29.

Yannakakis GN and Hallam J (2006) Towards capturing and enhancing entertainment in computer games. *Advances in Artificial Intelligence* 3955: 432–442.