Planning-Based Social Partners for Children with Autism

Sara Bernardini
Department of Informatics
King's College London
London, UK, WC2R 2LS
sara.bernardini@kcl.ac.uk

Kaśka Porayska-Pomsta
London Knowledge Lab
Institute of Education
London, UK, WC1N 3QS
k.porayska-pomsta@ioe.ac.uk

Abstract

This paper describes the design and implementation of a planning-based socially intelligent agent built to help young children with Autism Spectrum Conditions acquire social communication skills. We explain how planning technology allowed us to satisfy the requirements relating to the agent's design that we identified through our consultations with children and carers as well as our review of best practices for autism intervention. We discuss the design principles we implemented, the engineering challenges we faced and the lessons we learned in building the pedagogical agent. We conclude by presenting extensive experimental results concerning the agent's efficacy.

1 Introduction

In this paper, we present a best practice approach to designing and implementing a planning-based virtual agent, called Andy, that can act credibly both as a peer and as a tutor in helping young children with Autism Spectrum Conditions (ASCs) develop social communication skills.

Autism is a spectrum of neuro-developmental conditions that affects three main areas ("triad of impairments" (American Psychiatric Association 2000)): (i) *communication*: problems with verbal and non-verbal language; (ii) *social interaction*: problems with recognising and understanding other people's emotions and with expressing their own emotions; and (iii) *patterns of restricted or repetitive behaviours*: problems with adapting to novel environments.

We focus on enhancing the *social communication* competence of children with ASCs because this is the domain with which they typically have the most difficulty (Prizant et al. 2003) and because recent studies indicate that individuals with ASCs and their caregivers consider support in this area as the most desirable feature of technology-enhanced intervention (Putnam and Chong 2008). Social communication involves the ability to coordinate and share attention, intentions, and emotions with others and a capacity for engaging in reciprocal interaction by understanding and using verbal and non-verbal means.

Our pedagogical agent operates in a virtual environment, called ECHOES, and its most recent extension called SHARE-IT, which have been created for real-world use in schools and at home as part of children's everyday activities. At school, the interaction between the child and the agent is facilitated by a 42" multitouch LCD display with eye-gaze tracking, whereas at home by iPads, tablets and PCs.

The paper is organised as follows. Section 2 explains why children with ASCs may benefit from interacting with autonomous virtual agents. Section 3 establishes a set of requirements for our agent. In Sections 4 and 5, we present the details of the design and the implementation of the agent and the challenges we faced in building it. We conclude by discussing the evaluation of the agent within the ECHOES virtual environment.

2 Agent Technology for Autistic Children

Several studies show that the majority of autistic people exhibit a natural affinity with technology and a positive attitude towards computer-based training (Putnam and Chong 2008). Software programs offer a predictable and structured environment that can accommodate their need for organisational support and their preference for routine and repetitive behaviours (Murray 1997). Among all available technologies, virtual agents are believed to offer particular benefits to children with ASCs for several reasons (Parsons and Cobb 2011). Autistic individuals find real social interactions stressful and intimidating due to their unpredictable and judgemental nature. Hence, traditional educational settings that involve being part of a classroom and interacting with other students and teachers are often challenging for them. The anxiety linked with social interaction can be mitigated by the use of artificial tutors and peers, which can be programmed to act tirelessly, consistently and positively towards the child regardless of the child's behaviours. Artificial tutors can support individualised learning, which is paramount for children with ASCs. An appropriately designed virtual tutor can meet individual children's needs and allow them to proceed at their own pace. Studies show that autistic children who were taught by a virtual human retain more information than they would in a traditional classroom setting (Grynszpan, Martin, and Nadel 2008). In addition, virtual agents are more likely to promote generalisation of the learned skills from the virtual to the real world because they allow the child to rehearse behaviours in role-play situations and to exercise the same skill in different scenarios, from simple and structured situations to increasingly more complex and unpredictable contexts (Tartaro and Cassell 2008; Bosseler and Massaro 2003; Parsons and Cobb 2011).

Intelligent virtual agents have generally proven valuable for training, learning and entertaining purposes. Planning technology has been often used to confer autonomous and believable behaviour to synthetic characters, e.g. (Cavazza, Charles, and Mead 2002; Kenny et al. 2007; Aylett et al. 2009), as well as to improve the user narrative experience in interactive storytelling systems, e.g. (Young 1999; Riedl, Thue, and Bulitko 2011). The techniques developed in these contexts are not always immediately applicable in our scenario due to the specific characteristics of our target population. Autistic children need a responsive agent that can provide a natural real-time interaction and, at the same time, engage them in structured learning activities, whereas state-of-the-art systems tend to focus on either one modality or the other.

Despite the growing interest in the potential of artificial agents for autism intervention, the efforts have focused primarily on agents with little or no *autonomy*. Typically, virtual agents are either authored a priori or directly controlled by a practitioner through a control panel (e.g. (Tartaro and Cassell 2008)). The only projects that have devoted attention to autonomy are the Thinking Head (Milne et al. 2010), a 3-D computer-animated talking head that teaches social skills by realistically portraying facial expressions, and Baldi and Timo (Bosseler and Massaro 2003), also talking heads that deliver language and speech training. We believe that autonomous agents carry significant potential for autism intervention because they can contribute to the intensive one-on-one support that children need while easing the demand for such support from practitioners and parents. Autonomous agents can complement the traditional intervention methods by undertaking repetitive tasks and providing on-demand intervention and therefore leaving only the most complex aspects of face-to-face interventions to human practitioners. On-demand intervention can be particularly beneficial given abnormal sleep patterns and frequent need for intensive one-to-one support. The approach presented in this paper focuses on the development of a *fully autonomous* agent, i.e. an agent that is capable of independently deciding how best to act in order to achieve a set of high-level goals delegated to it. As deliberative behaviour is a fundamental component of autonomy, we placed planning technology at the core of our agent, as we explain in the following sections.

3 Pedagogical Requirements for the Agent

Our goal was to create an artificial social partner that could act credibly both as a peer and as a tutor for ASCs children and, as a result, deliver the educational and interpersonal support needed by these children to develop social communication skills. In order to identify the defining characteristics of social interaction between an agent and a child, we drew from consultations with users and best-practice autism intervention. Specifically, we organised two knowledge elicitation workshops involving thirty practitioners with extensive experience in autism and three high functioning teenagers with ASCs. Through the aid of storyboarding tools, group discussions and individual interviews, we assembled our requirements for the agent, which we then validated against SCERTS (Prizant et al. 2003), a comprehensive approach to social communication assessment and intervention in autism. SCERTS identifies the particular skills that are essential for successful social communication and, we argue, necessary for an *ideal* virtual agent to act as a credible social partner of children with ASCs. These skills are encapsulated in three domains: (i) *Social Communication (SC)*: spontaneous and functional communication, emotional expression, and secure and trusting relationships with children and adults. (ii) *Emotional Regulation (ER)*: the ability to maintain a well-regulated emotional state to cope with everyday stress and be available for learning and interacting. (iii) *Transactional Support (TS)*: the development and implementation of supports to help caregivers respond to the child's needs and interests, modify and adapt the environment, and provide tools to enhance learning. SCERTS breaks down each domain into a number of components and for each one provides a detailed description of the education objectives to be achieved, the strategies for intervention and the assessment criteria. We built on this *operationalisation* of social communication in designing our agent's behaviour and its interaction with the child. We enumerate these requirements below, while we explain how we met them in Section 4.

1. **Agent's Role:** As a *tutor*, the agent needs to be able to deliver support for: (a) "expanding and enhancing the development of a child's expressive communication system"; (b) "supporting a child's understanding of language as well as others' nonverbal behaviour"; (c) "supporting a child's sense of organisation, activity structure, and sense of time". On the other hand, when acting as a *peer*, the agent needs to provide children with interpersonal support by: (d) accommodating the children's preference for structure and predictability, while fostering initiation, spontaneity, and self-determination; (e) exposing the child to a positive interaction with a peer so that they can "benefit optimally from good language, social, and play models" (all quotes from (Prizant et al. 2003, p. 309)).
2. **Pedagogical Focus:** The agent needs to focus on the two sub-components of social communication that have been identified by SCERTS as the most challenging: (i) *Joint Attention:* ability to coordinate and share attention and emotions, express intentions, and engage in reciprocal social interactions by initiating/responding to bids for interaction; and (ii) *Symbol Use:* understanding meaning expressed through conventional gestures and words and ability to use nonverbal means to share intentions.
3. **Learning Activities:** All the activities that the agent proposes to the child need to share an "obvious unifying theme" in order to support shared attention and should be "meaningful and purposeful" (Prizant et al. 2006), in contrast with approaches where the activities are task-based and skills are trained in a repetitive fashion.
4. **Responsiveness:** The agent needs to be highly responsive. Responsiveness should range from simple physical

reactions to the ability to respond to the child's changing needs as well as cognitive and emotional states. The agent should always provide the children with positive feedback in order to reduce their anxiety related to social interactions and help them experience a sense of self-efficacy and achievement.

5. **Style of Interaction:** The agent should impart on autistic children an optimal interaction style, which "is one that provides enough structure to support a child's attentional focus, situational understanding, emotional regulation, and positive emotional experience, but that also fosters initiation, spontaneity, flexibility, problem-solving, and self-determination" (Prizant et al. 2003, p.309).

4 Agent's Design and Implementation

We argue that the recommendations for the agent's design described in Section 3 are in line with the classic agent theory of Wooldridge and Jennings (1995), whereby an autonomous agent should be equipped with: (i) *Pro-activeness*, i.e. an ability to exhibit goal-directed behaviour by actively trying to accomplish its goals and taking the initiative; (ii) *Reactivity*, i.e. the ability to perceive the changes in the environment and react to them in a timely manner; and (iii) *Social ability*, i.e. the ability to coordinate its actions with those of another agent - in our case the child. Pro-activeness is important to maintain the child's attentional focus and to foster motivation. Reactivity is fundamental to adapt to the children's changing needs as well as cognitive and affective states. Social ability is crucial to maximising the child's experience of a sense of self-efficacy in communicating with the agent. Therefore, we believe that an optimal interaction for ASCs children can be approximated by an autonomous agent augmented with social ability and characterised by the right balance between pro-activeness and reactivity. Below, we describe how we built this agent and the choices we made to fulfil the agent's requirements.

Learning Activities: Pursuant to Requirement no. 3, all the learning activities share a "unifying theme" in that they take place in a sensory garden populated by Andy and by interactive "magic" objects that react in unusual ways and turn themselves into other objects when either the agent or the child touch them in specific ways. For example, tapping the petals of a flower makes the flower become a floating bubble or a bouncy ball. This activity is meaningful because the sequence of action-reaction triggered by a specific gesture promotes the children's understanding of cause and effect, which is often impaired in individuals with ASCs. The agent can engage the child in two types of activities: (i) *goal-oriented* activities, with a clear sequence of steps and an easily identifiable end-goal; and (ii) *cooperative turn-taking* activities, with no clear end-goal and designed to foster social reciprocity, turn taking, and mutual enjoyment. Sorting a set of balls according to their colours is an example of goal-oriented activity, while growing flowers by shaking a cloud that produces rain constitutes a turn-taking activity. All activities are intended to be performed by Andy and the child in cooperation, with Andy assuming a more or less prominent role according to the particular learning activity's objective and the individual child's needs. For example, if the goal is *learning-by-imitation*, Andy will adopt a leading role and demonstrate different behaviours to the child. If the goal is *engaging-in-reciprocal-interaction*, Andy will wait and give the child an opportunity to initiate the interaction, before stepping in and doing so if the child hesitates.

Agent's Architecture and Planning Mechanism Among the various domain-independent agent architectures that have been proposed for building agents, FAtiMA (Dias and Paiva 2005; Aylett, Dias, and Paiva 2006) is ideally suited to fulfil the design requirements of our agent, because it integrates an affective appraisal system with a planning mechanism. A FAtiMA agent displays the reactive capabilities needed to obtain a responsive character (Requirement no. 4), the cognitive capabilities needed to provide the child with structured and goal-oriented activities (Requirements no. 1, 2 and 5) and the socio-emotional competence needed to help the child acquire social skills (Requirement no. 5).

The two main mechanisms controlling a FAtiMA agent are *appraisal* and *coping*. The agent experiences one or more of the 22 emotions of the OCC model (Ortony, Clore, and Collins 1988) based on its appraisal of the current external events against the backdrop of its own goals as well as its subjective tendencies to experience certain emotions instead of others. The agent deals with these emotions by applying *problem-focused* or *emotion-focused* coping strategies. Both the appraisal and the coping work at two different levels: the *reactive* level, which affects the short-term horizon of the agent's behaviour, and the *deliberative* level, which relates to the agent's long term goal-oriented behaviour. The core of the deliberative layer is a Partial-Order-Causal-Link (POCL) continuous planner (Weld 1994), which constantly generates plans, triggers the execution of actions and monitors all events in order to detect whether actions are accomplished or have failed.

A FAtiMA agent is characterised by: (i) a set of *goals*; (ii) a set of *operators*; and (iii) an affective system which includes: (a) *emotional reactions*, rules to determine how generic events are appraised by the agent; (b) *action tendencies*, to represent the agent's impulsive actions to different emotional states; (c) *emotional thresholds*, to specify the agent's resistance to different emotions; and (d) *decay rates* for emotions, to determine how fast an emotion decays over time. A goal is defined by: (i) *preconditions*, which determine when the goal becomes active; (ii) *success conditions*, which represent the world state when the goal has been achieved; (iii) *failure conditions*, which determine when the goal fails, once activated; (iv) *importance of success and failure*, which specify the agent's goal preferences. When the preconditions of one goal are verified, the goal becomes active and the deliberative layer creates an *intention* to reach that goal. An intention is a concrete instantiation of a goal. If any of the failure conditions becomes true while the goal is active, the goal fails and the corresponding intention is removed. An intention is characterised by: (i) *goal*, the instantiated goal; (ii) *emotions*, the emotions generated by the intention to reach the goal; (iii) *plans*, a list of alternative plans to reach the goal, which are synthesised by the planner. When an intention is created, an empty plan is stored in the plan list. This empty plan contains an initial step, which is associated with the current world state, and a final step, which includes the goal success conditions. When the planner selects an intention as the next one to fulfil, alternative partial plans are built and added to the list until a final plan is found. FAtiMA operator specification is similar to STRIPS: preconditions and effects need to be provided for each operator. In addition, probabilities are associated with effects, so that one can model both certain and uncertain effects. Each operator has two additional fields that indicate if the action can be performed by a different agent and the associated probability of the action being executed by such agent. This mechanism allows a FAtiMA agent to account for the actions of other agents when constructing a plan. We exploit this method to build plans that take into account the actions of the child in response to the agent's actions. Plans in FAtiMA have the traditional structure of POCL plans: (i) a set of *actions*; (ii) a set of *ordering constraints* defining a partial order on the actions; (iii) a set of *binding constraints* on the actions' parameters; (iv) a set of *causal links*; and (v) a set of *flaws*, including open preconditions, unbound variables and causal link threats. The plan probability of success, P(plan), is determined by multiplying the conditional probability of all the effects that appear in the causal links and the probability of execution of the actions performed by other agents.

FAtiMA interleaves planning and execution so that there is always an appropriate action that the agent can execute. In particular, FAtiMA has a continuously running cycle in which the following steps are performed: (1) Monitor the execution of the current action and, when the action ends, update the effect probabilities, the partial plan and the world state accordingly; (2) Check whether new goals get activated and, if so, generate the corresponding intentions; (3) Select the intention that generates the strongest emotions as the one to focus on; (4) Select the best plan built so far associated with the selected intention, where the best plan is given by the following heuristic function: h(Plan) = (1 + numberOfSteps + numberOfOpenPreconditions + numberOfCausalLinkThreats * 2) / P(plan). (5) Apply both problem-focused and emotional-focused strategies to this plan; and (6) Check whether any of the active instantiated goals has succeeded or failed, generate the corresponding emotions and update the set of intentions accordingly.

The agent adopts an emotion-focused strategy when, based on the emotions it is experiencing, it tries to change its interpretation of the external events, for example by changing the importance of its goals or the probabilities of its actions' effects. The affective system acts as a powerful heuristic for the planner because it controls the importance of goals and the intention selection. On the other hand, when the agent uses a problem-focused coping strategy, it tries to reduce the dissonance between its goals and the external events by acting on the external world to change it. The problem-focused coping strategies are realised through the POCL planner, which starts from an initial empty plan and incrementally refines it by adding actions to it, ordering such actions and binding open variables until a final plan is found. When the planner resolves a flaw, it stores all the alternative resulting plans so that it can always choose the best plan to work on during the next cycle. When a consistent plan is found, it starts to be executed. In each cycle, the planner is allowed to tackle only one flaw or to prompt the execution of one action, so it usually requires several cycles to build and execute a plan. As several reappraisals of the same plan are performed before the plan is actually executed, the planner is able to constantly switch between competing goals and to react to the current situation appropriately.

Authoring the Agent: Each learning activity has a FAtiMA agent model associated with it. All these models share the same specification of the agent's affective system, so that the agent can maintains the same personality between sessions and establish a trusting relationship with the child. Andy is a positive, motivating and supportive character, which we crafted by manipulating emotional reaction rules and action tendencies as well as the emotional thresholds and decay rates of the OCC emotions. For example, the child smiling or taking the turn has a very high desirability to Andy, whereas the child not playing with Andy has low desirability. In addition, Andy has a tendency to be happy, thanks to its low happiness threshold and slow happiness decay. We control Andy's facial expressions and gestures through the specification of Andy's action tendencies. For example, the agent smiles when it is happy, opens its mouth when it is surprised, nods when it is satisfied, and so on. A short extract from Andy's personality model follows:

```
<EmotionalThresholds emotion="Love" threshold="1" decay="1" />
<EmotionalThresholds emotion="Anger" threshold="8" decay="2" />
<ActionTendency action="SelfGiveThumbsUp">
<ElicitingEmotion type="Joy" minIntensity="10">
<CauseEvent subject="User" action="TookTurn" target="*" />
</ElicitingEmotion>
</ActionTendency>
<EmotionalReaction desirability="8" desirabilityForOther="8">
<Event subject="User" action="Smile"/>
</EmotionalReaction>
```

While Andy's personality does not change between activities, its goals and action strategies are specified for each learning activity based on: (i) the high-level pedagogical goals on which the activity focuses; and (ii) the specific narrative content of the activity itself. For example, if the high-level goal of an activity is "Engage in reciprocal interaction" and the content of the activity involves picking flowers from the garden, one of the low-level goals of the agent will be to fill a basket with flowers together with the child, whereas its action strategies will demonstrate to the child different ways of engaging in reciprocal interaction, by choosing, for example, between pointing at a flower, looking at it, or saying "Your turn!". The following extract shows the low-level goal of making pots available to the child so that flowers can be grown inside them during a pot-stacking activity:.

```
<ActivePursuitGoal name="makePotAvailableForPotStacking()">
<PreConditions>
<Property name="PotStacking(isChosenAct)" op="=" value="True"/>
<Property name="RemoveFlowerFromPot()" op="=" value="True"/>
</PreConditions>
<SuccessConditions>
<Property name="RemoveFlowerFromPot()" op="=" value="False"/>
<Property name="FreePot()" op="=" value="True"/>
</SuccessConditions>
<FailureConditions>
<Property name="[User]RemoveFlower()" op="=" value="True"/>
</FailureConditions>
</ActivePursuitGoal>
```

Given that the focus of ECHOES/SHARE-IT is on supporting joint attention and symbol use (Requirement no. 2), the agent's actions are either concrete demonstrations of the related skills or actions performed to invite the child to practice those skills. Specifically, we define the joint attention and symbolic use in terms of three component skills: (i) Responding to bids for interaction; (ii) Initiating bids for interaction, and (iii) Engaging in turn taking. Our agent is able to perform these skills in three different ways: (i) Verbally by using simple language or key phrases (e.g., "My turn!" and "Your turn!" for turn-taking); (ii) Non-verbally through gaze and gestures, such as pointing at an object from a distance or touching the object; (iii) By combining verbal and non-verbal behaviours. The following extract from Andy's operator set describes a verbal bid for interaction:

```
<Action name="SelfVerbalBid([obj],[act],[purpose],[repeat])"
 prob="1">
<PreConditions>
<Property name="[act](isChosenActivity)" op="=" value="True"/>
<Property name="verbal(isChosenBidType)" op="=" value="True"/>
<Property name="[obj](objectIsTarget)" op="="  value="True"/>
<Property name="[purpose](isChosenPurpose)" op="=" value="True"/>
<Property name="[repeat](isChosenRepeat)" op="=" value="True"/>
</PreConditions>
<Effects>
<Effect prob="1.0">
<Property name="madeBid()" operator="=" value="True"/>
</Effect>
</Effects>
</Action>
```

Andy is able to make requests, to greet the child by name, to comment on actions or events happening in the garden and to use exploratory actions on objects, e.g. to explore the properties of the magic objects populating the garden. This variety of behaviours makes the interaction dynamic enough to keep the child engaged and to foster generalisation, while retaining a degree of predictability that is essential to support the child's attentional focus. In compliance with Requirement no. 3, Andy always provides the child with positive feedback, especially if the child correctly follows the agent's bids for interaction in task-based activities. If the child does not perform the required action, the agent first waits for the child to do things at their own pace and then intervenes by demonstrating the action and encouraging the child to try again. To provide organisational support, the agent always explains a new activity to the child by using simple language and precise instructions (e.g., "Let's pick ten flowers").

We show below a simple example of a sequence of steps associated with an intermediate plan formulated by the planner during the pot-stacking activity:

```
[SELF]WalkTo(pot5);
[SELF]PickUpPot(pot5);
[SELF]StackPot(pot5,pot3);
[SELF]LookAround();
[SELF]MakeComment(potStacking);
[SELF]Wait();
[CHILD]TakeTurn(potStacking);
```

5 Challenges and lessons learned

In building our agent, we chose FAtiMA from the numerous agent technologies we investigated because it was one of the few architectures able to deal with both the deliberative and the affective sides of the agent, which is essential in our application. However, using FAtiMA to create an interactive system that would scaffold autistic children social skills presented us with a number of challenges, which we illustrate below together with the lessons we learned in the process. These challenges are not specific to FAtiMA, but are common to many other state-of-the-art planning systems and agent architectures.

Knowledge Processing: To operate correctly and efficiently, the planner relies on manipulating knowledge at a high-level of abstraction generated by other components in the architecture that are charged with receiving timely sensor data from the external world, processing them at the right level of abstraction and passing them on to the appropriate modules in the system. The planner reasons about what actions the agent needs to perform in order to appropriately support the child's development of social skills, but it neither interprets the child's actions in terms of their social interaction meaning nor assesses the cognitive and affective state of the child. For example, if the child touches a flower pot during a turn-taking activity with Andy, the planner will receive the information that the child has appropriately taken his turn and, after repeating the activity several times, now understands turn-taking, but it will not draw these conclusions by itself. As is the case for many other complex autonomous architectures (e.g. (Doherty, Kvarnström, and Heintz 2009)), our agent requires knowledge processing on many levels of abstractions and the planner produces intelligent behaviour for the agent in cooperation with other components of the system that continuously provide it with appropriate information. Structuring domain knowledge at different levels of abstraction and engineering a system where several components manage and share different layers of knowledge is a challenging problem. To solve this problem, we equipped ECHOES/SHARE-IT with three additional components, which together with FAtiMA forms the *intelligent engine*: (i) the pedagogic component; (ii) the social-communication component; and (iii) the child model.

For each session, the *pedagogic component* establishes the initial state and the relevant goals and passes this information on to the planner. While the overall set of goals within which it can choose is formulated on the basis of the SCERTS framework, both the initial situation and the specific set of goals for each user in any given session are decided on the basis of the user's profile and their interaction history with the system. After delegating the session goals to the agent, the pedagogic component leaves the agent free to interact with the child without interfering. It does, however, monitor the unfolding of the events and receives input from the user model. If the interaction between the child and the agent diverges significantly from the pedagogical goals of the session, the pedagogic component can intervene to keep the interaction on track. It can, for example, suspend the execution of the current plan, influence how the planner constructs a new plan, change the overall goals of the session and even drop these goals, if appropriate. Conceptually, the pedagogic component acts similarly to the "drama manager" in interactive storytelling systems (Riedl, Saretto, and Young 2003), although its role is more limited.

The *social-communication component* attributes a meaning to the child's actions from a social communication standpoint. This component builds on low-level information concerning the specific gestures that the child has performed (e.g. the child has offered an object to the agent) and brings this information to a higher level of abstraction by linking gestures to their social meaning (e.g. the child has responded to a request from the agent to give it an object). This component is based on a set of rules extracted from the SCERTS framework and the specific context of the interaction between the child and the agent.

The *child model* is a user model that estimates the cognitive and affective state of the child in real time and constantly feedbacks this information to the other components of the intelligent engine whenever a change in such a state is detected. The child model supports Andy in making informed decisions about what to do next based on the current mental state of the child and allows Andy to react appropriately to the child's intentions, needs and desires. Hence, the child model is key for satisfying Requirements no. 4 and 5. The child model infers the mental states of the child based on real-time information coming from the touch and eye-gaze systems and produces output at two levels: cognitive and affective. The cognitive assessment is facilitated by a rule-based engine that estimates the extent to which the child has achieved the pedagogical goals associated with the session. The rules are based on the SCERTS model, which provides clear guidelines and precise timing constraints to establish whether the child has mastered specific skills in relation to joint attention and symbolic use. The affective assessment is facilitated by a combination of supervised and unsupervised learning techniques that are used to estimate the child's level of engagement with the system among five different categories, from complete engagement to total disengagement. Engagement is an important indicator of the affective state of a child because disengagement is usually linked with boredom and anxiety, whereas engagement with interest and excitement. We faced significant challenges in interpreting the child's mental state accurately, which can be largely ascribed to the naturalistic context in which the system was used: with the child standing and free to move around, it was difficult to collect reliable data through the touch and eye-tracking systems. In order to deal with the child model failures, we supplemented the system with a wizard-of-oz control panel, and used this version of the system for the evaluation studies reported in Section 6. Besides the technical challenges, we also faced a more fundamental question. User modelling relies on common features and behaviours across all the users for constructing the base models. Yet, this may not be fully feasible for contexts, such as autistic intervention, where every user represents a different and individual case and where the domain knowledge does not lend itself to being represented in terms of "right" or "wrong" solutions. It seems that more intimate profiles for the children may need to be constructed in this context by supplementing automatic user modelling techniques with a direct involvement of teachers, parents and children themselves.

Real-Time Constraints: Our system aims to provide a spontaneous and unconstrained real-time interaction between the user and the agent. Children can touch the screen whenever they want to interact with Andy and Andy needs to react timely and appropriately. We encountered a major challenge in meeting the real-time constraints emerging in this kind of scenario, as FAtiMA is not well suited to the interactivity required of an agent situated in a fast-paced dynamic world. This is probably due to the fact that FAtiMA was developed in the context of the FearNot! project (Aylett et al. 2009), where synthetic agents can freely interact with one another, but not with the user. In FearNot!, interactions between the system and the user happen through text boxes that appear on the screen only at specific times during which agents do not act. However, this is not an isolated problem of FAtiMA, since many other state-of-the-art architectures are also unable to cope with hard real-time constraints.

FAtiMA possesses two characteristics that are generally considered essential for a real-time agent. Firstly, it integrates reactive and deliberative capabilities so that the agent can respond reflexively to events that occur quickly and yet take the time to reason more deliberately to solve goal and resource management problems. Secondly, it is based on a *continuous planning* strategy, which interleaves planning and execution. Although these characteristics proved very useful in our context, in ECHOES/SHARE-IT there is the additional difficulty that the external world changes quickly, frequently and unpredictably due to the actions performed by the child. Pressured by the high variability of the environment, FAtiMA constantly formulates new goals and quickly abandons them so that plans are rarely executed to completion. This prevents the agent from behaving intelligently and delivering a natural, 'face'-to-face interaction with the child in support of long-term pedagogical objectives.

In highly dynamic environments and situations in which replanning happens frequently and needs to be fast, a number of strategies can help. (i) *Anytime planning*: the planner is able to immediately return a usable solution every time it is interrupted; the quality of the plan improves as processing time increases (Hawes 2001; Zilberstein 1996). (ii) *Incremental and refinement planning:* the planner is able to reuse the results of previous planning efforts to plan more efficiently or to repair a plan that is no longer executable. When using an incremental strategy, plans are only partially elaborated at first and then refined when the agent starts executing them (Pollock 2006). In this way, recent information about the state of the world can be used to make the plan more strictly contingent on the current situation. (iii) *Expectation-based monitoring:* the agent incorporates a monitoring mechanism that provides early warning of plan failure based on the expected probability of execution of actions in the plan. These early warnings allow the planner to have more time to adjust and more flexibility in the range of possible responses (Doherty, Kvarnström, and Heintz 2009).

Goal Management: In contrast with traditional planning, our agent needs to deal with a large number of potential goals, a subset of which can be active at the same time. Simultaneously active goals might correspond to one pedagogical objective expressed at different levels of abstraction or to multiple possible routes to satisfying that same objective. In addition, goals might have different varying importance or urgency and different life-cycles, some being long-term, others being just temporary. For example, supporting the child's bid for interaction is a long-term goal with high importance, while filling the basket with flowers is a goal contingent on the specific activity of picking up flowers from the garden and is therefore less important. The selection of the goal (or conjunction of goals) the planner should first attend to is a well-known problem in planning (Hawes 2011; Pollack and Horty 1999). In many real-world systems, goal management is as important as plan generation. The goal selection process should ensure that the agent acts to best satisfy its current needs in light of the available resources and other possible contextual restrictions.

In principle, our scenario could be easily modelled as an *over-subscription* problem in which numerous goals with different values in terms of importance and urgency are active at the same time and the agent needs to choose which goals to pursue given its limited resources. However, the FAtiMA planner, as well as the majority of state-of-the-art planners, does not include a mechanism to solve over-subscription problems. In FAtiMA, goal selection is determined by the affective appraisal system. The goals that generate the strongest emotions in the agent are the ones that require the most attention, and thus they are selected by the planner for execution. However, whenever the agent experiences negative emotions, the importance of the current goal is lowered and the goal might be dropped entirely. Although we recognise that in general emotions can be a powerful controlling mechanism of the agent's intentions (Sloman 1998), the emotion-centred goal management strategy employed in FAtiMA is not always valid in our context. In fact, in ECHOES/SHARE-IT, the majority of the goals correspond to pedagogical objectives that the agent needs to achieve to support the child's learning process. These goals cannot be abandoned because they are at the core of the system's mission. Ideally, we would like the agent to possess goal maintenance and goal reconsideration mechanisms for deciding whether to persist in the achievement of the goal, to suspend the goal for a period of time and resume it at a later stage, or to drop the goal altogether. However, this is a complex mechanism that FAtiMA and many other state-of-the-art agent architectures do not possess.

Quality of Plans: The FAtiMA plan selection strategy is problematic for our domain. FAtiMA selects the plan that takes the least time to achieve the goal and that has the highest probability of success based on previous attempts to perform the actions in the plan. Hence, when a plan contains a number of actions that have previously failed, its score is low and it will not be selected for execution. In addition, if the probability of a plan under execution drops under a certain threshold, the plan is abandoned. While this mechanism can be appropriate in domains where not many failures are expected, in our scenario failures occur frequently for two reasons: the system works in real-time and the agent engages the child in tasks requiring social skills that the child lacks at first and needs time to acquire. In this scenario, initial attempts to execute a plan are likely to fail. However, the pedagogical agent, charged with supporting the child in acquiring social skills, should not drop the goals targeted by plans that have failed but should instead behave as a tireless companion, repeating bids for interaction regardless of how many times those bids have previously failed. We therefore need a plan metric capable of evaluation plans based on their pedagogical validity and not on customary performance measures such as time and probability of success. The importance of focusing on plan quality has been recognised by the planning community with the introduction of PDDL3 (Gerevini and Long 2006), although few planners are currently able to handle PDDL3 domains.

Authoring Characters: FAtiMA characters are complex to author since their behaviours emerge from a combination of multiple factors. For the final behaviour of the characters to be as one intended, not only do operators and goals need to be carefully defined, but *ad hoc* values also need to be assigned to emotional reactions, action tendencies, emotional thresholds and emotion decay rates. Since there are no conventional definitions of such values, authors have to adjust them through trial and error. This process of fine-tuning the domain model is often time-consuming and cumbersome. A number of solutions to this problem have been proposed, as the use of authoring tools in which characters are trained through rehearsal, rather then explicit programming (e.g. (Kriegel and Aylett 2008)) and the use of different theoretical frameworks that help the author achieve some of the behaviours without having to explicitly author them (e.g. (Lim et al. 2012)).

6 Experimental Results

Although we faced a number of challenges in implementing our agent, we were able to obtain a fully functional system. We carefully engineered the domain models and relaxed the hard real-time requirements by significantly slowing down the pace of the interaction between the children and the agent. Indeed, our formative evaluation studies with an initial prototype of ECHOES showed that a fast-paced interaction was too demanding for autistic children, who can be extremely sensible to auditory and visual stimuli. FAtiMA has been fully integrated in the ECHOES/SHARE-IT environment and the planner is able to produce plans fast enough for the children to be able to enjoy the interaction with Andy. Below, we focus on our extensive evaluation of ECHOES as the evaluation of SHARE-IT is in progress.

To assess the impact of Andy and ECHOES on social communication in children with ASCs, a large scale multi-site intervention study was conducted. The system was deployed in five schools in the UK. 19 children with ASCs participated in the study during which they played with ECHOES for 10 to 20 minutes, several times a week over an eight week period. To assess each child's initial social communication skills a structured table-top turn-taking activity was conducted and their behaviours assessed from video recording of the session. At the end of the intervention, a second table-top session was conducted to assess generalisation of the social behaviours learned during use of ECHOES. The SCERTS Assessment Protocol (SAP) (Prizant et al. 2006) was modified into a finer-grained coding scheme that could be applied to videos of children's interactions with Andy. The modified SAP coding scheme contains 16 main behavioural categories. Due to space limitations, we will focus only on two main social behaviours, which are severely impaired in children with ASCs: responding to and initiating bids for interaction. Fifteen minute periods during which the children interacted with Andy were identified for analysis from the beginning, middle and end of the intervention period. Each video was blind-coded by a coder trained in the modified SAP coding scheme. Video annotations were applied in ELAN (video annotation tool) and moderated by a second coder.

Child's response to social partner The mean probability that the child responded to the practitioner's bids for interaction during the table-top pre-test was 0.66 (SD=0.17). After the intervention the probability was 0.71 (SD=0.14). This slight increase in responses between the pre and post table-top test was not significant ($t(14)=-1.637$, $p=.124$, n.s.). However, during ECHOES the probability that the child responded to the practitioners bids for interaction increased significantly relative to the table-top pre-test: beginning = 0.73 (SD=0.21, $t(16)=-3.107$, $p<.01$), middle = 0.74 (SD=0.19, $t(16)=-3.387$, $p<.01$), end = 0.79 (SD=0.21, $t(16)=-4.072$, $p<.001$). This increase may suggest a comfort with the ECHOES environment that elicited a level of responsiveness in the child not observed during the table-top activity. As Andy is a critical part of ECHOES, we can assume its presence contributed to this improvement. Across the three ECHOES sessions, the proportion of Andy's initiations responded to by the child showed a slight but non-significant decrease: beginning = 0.57 (SD=0.22), middle = 0.53 (SD 0.25), end = 0.49 (SD 0.23); all ts<1. Given the increasing complexity of the learning activities and their dependence on turn-taking with Andy across the three sessions, the relative stability of the child's response rate to agent initiations is reassuring and may suggest the potential for the response rate to increase given future refinement of Andy's intelligence.

Child's initiations to social partner An advanced social behaviour rarely observed in ASCs children is the initiation of social interactions. The frequency with which the child initiated an interaction during the table-top pre-test was low, 9.65 times (SD 7.78) and did not change by the post table-top session, 9.93 times (SD 11.5): $t(18)=.154$, $p=.88$, n.s.The number of initiations to the human practitioner numerically increased across the three ECHOES sessions from 14.06 (SD=18.3) to 16.29 (SD=25.5) and 17.94 (SD=25.8) but the large variance across individual children rendered this increase non-significant. Initiations to Andy also numerically increased across the three ECHOES sessions from 4.89 (SD 8.05) to 6.68 (SD 7.68) and 9.63 (SD 13.74). Unfortunately, this difference did not reach significance (beg-end: $t(18)=-1.719$, $p=.103$, n.s.). Eight children increased their number of initiations to Andy, seven produced the same number and only four decreased. This suggests that the heterogeneity in our ASCs population may make it difficult to identify a group increase in initiations. However, an encouraging indication of the child's increasing social engagement with Andy can be seen in the decreasing difference in the frequency of initiations the child made to Andy compared to the human practitioner. During the beginning and middle ECHOES sessions the mean number of initiations made to Andy is significantly lower than the number made to the human practitioner (beg: $t(18)=2.215$, $p<.05$; mid: $t(18)=1.943$, $p=.068$, i.e. marginal), but by the final ECHOES session this difference had disappeared ($t(18)=1.621$, $p=.122$, n.s.). This increase might indicate that the child was increasingly regarding Andy as socially authentic partner who they could interact with. Anecdotal evidence supporting this hypothesis comes from a number of children who showed no initial interest in Andy, but spontaneously talked to it and even waved when it walked on the screen in later sessions. Such behaviours were extremely surprising to teachers and support workers within the school who believed the child in question to be non-communicative.

7 Conclusions

In this paper, we present our approach to developing, deploying and evaluating a planning-based pedagogical agent that helps children with ASCs develop social communication skills. Designing a social partner for children, especially autistic children, increases the need for credibility and believability of the agent. We argue that such characteristics come from the ability of the agent to act autonomously and to adapt to individual children in real-time. We believe that the construction of a robust agent architecture that brings together deliberative and emotional reasoning, real-time reactivity, flexible goal management and hierarchical knowledge processing is still an open problem. Despite the difficulties that we encountered in the development of our agent, we managed to produce a fully-working prototype that we deployed with a significant number of children and the efficacy of which we evaluated on the basis of a large number of real-world interactions. To the best of our knowledge, the ECHOES evaluation represents one of the first major evaluations of a pedagogical virtual companion for autistic children conducted in real-school contexts and involving a significant number of children. Although presently we can only report coarse-grained analysis of children's behaviours in relation to Andy, there is evidence of some children having benefited from their exposure to Andy and the ECHOES environment as a whole. Specifically, the experimental results show that, although the number of initiations children make to Andy when they first use ECHOES is significantly lower than the number of initiations they make to the practitioner, this difference disappears by the final session. A possible interpretation of this phenomenon is that Andy's reciprocal interactions with children and its critical role within the learning activities are responsible for eliciting spontaneous social behaviours in the children.

Acknowledgments

ECHOES was funded by EPSRC and ESRC (grant: RES-139-25-0395-A). SHARE-IT is funded by EPSRC (grant: EP-K012428-1). We are grateful to Dr. T. J. Smith for his crucial help in analysing the experimental results, Dr. K. Avramides for her contribution to implementing the ECHOES agent and the entire ECHOES project team.

References

American Psychiatric Association. 2000. *Diagnostic and Statistical Manual of Mental Disorders*. Fourth Edition, Text Revision (DSM-IV-TR).

Aylett, R.; Paiva, A.; Dias, J.; Hall, L.; and Woods, S. 2009. Affective Agents for Education Against Bullying. In *Affective Information Processing*. Springer. 75–90.

Aylett, R.; Dias, J.; and Paiva, A. 2006. An affectively-driven planner for synthetic characters. In *Proc. of International Conference in Automated Planning and Scheduling (ICAPS-06)*. AAAI Press.

Bosseler, A., and Massaro, D. 2003. Development and evaluation of a computer-animated tutor for vocabulary and language learning in children with autism. *Journal of Autism and Developmental Disorders* 33(6):653–672.

Cavazza, M. O.; Charles, F.; and Mead, S. 2002. Character-based interactive storytelling. *IEEE Intelligent Systems* 17(4):17 – 24.

Dias, J., and Paiva, A. 2005. Feeling and Reasoning: A Computational Model for Emotional Characters. In *Progress in Artificial Intelligence*, volume 3808 of *Lecture Notes in Computer Science*. Springer Berlin, Heidelberg. 127–140.

Doherty, P.; Kvarnström, J.; and Heintz, F. 2009. A temporal logic-based planning and execution monitoring framework for unmanned aircraft systems. *Autonomous Agents and Multi-Agent Systems* 19:332–377.

Gerevini, A., and Long, D. 2006. Plan constraints and preferences in PDDL3. In *ICAPS Workshop on Soft Constraints and Preferences in Planning*.

Grynszpan, O.; Martin, J.-C.; and Nadel, J. 2008. Multimedia interfaces for users with high functioning autism: An empirical investigation. *International Journal on Human-Computer Studies* 66(8):628–639.

Hawes, N. 2001. Anytime planning for agent behaviour. In *Proceedings of the Twelth Workshop of the UK Planning and Scheduling Special Interest Group*, 157–166.

Hawes, N. 2011. A survey of motivation frameworks for intelligent systems. *Artificial Intelligence* 175(5-6):1020 – 1036.

Kenny, P.; Hartholt, A.; Gratch, J.; Swartout, W.; Traum, D. R.; Marsella, S.; and Piepol, D. 2007. Building Interactive Virtual Humans for Training Environments. In *Proceedings of the Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC)*.

Kriegel, M., and Aylett, R. 2008. Emergent Narrative as a Novel Framework for Massively Collaborative Authoring. In *Proceedings of the 8th International Conference on Intelligent Virtual Agents*, 73–80.

Lim, M. Y.; Dias, J.; Aylett, R.; and Paiva, A. 2012. Creating adaptive affective autonomous NPCs. *Journal of Autonomous Agents and Multi-Agent Systems* 24(2):287–311.

Milne, M.; Luerssen, M.; Lewis, T.; Leibbrandt, R.; ; and Powers, D. 2010. Development of a virtual agent based social tutor for children with autism spectrum disorders. In *Proc. of the International Joint Conference on Neural Networks*, 1–9.

Murray, D. 1997. Autism and Information technology: Therapy with Computers. In Publishers, D. F., ed., *Autism and Learning: A Guide to Good Practice*. Brookes. 100–117.

Ortony, A.; Clore, G. L.; and Collins, A. 1988. *The Cognitive Structure of Emotions.* Cambridge University Press.

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.

Pollack, M. E., and Horty, J. F. 1999. There's More to Life Than Making Plans: Plan Management in Dynamic, Multi-Agent Environments. *AI Magazine* 20(4):71–84.

Pollock, J. L. 2006. Against Optimality: Logical Foundations for Decision-Theoretic Planning in Autonomous Agents. *Computational Intelligence* 22(1):1–25.

Prizant, B.; Wetherby, A.; Rubin, E.; and Laurent, A. 2003. The SCERTS model: A Transactional, Family-Centered Approach to Enhancing Communication and Socioemotional Ability in Children with Autism Spectrum Disorder. *Infants and Young Children* 16(4):296–316.

Prizant, B.; Wetherby, A.; Rubin, E.; Laurent, A.; and Rydell, P. 2006. *The SCERTS® Model: A Comprehensive Educational Approach for Children with Autism Spectrum Disorders*. Brookes.

Putnam, C., and Chong, L. 2008. Software and technologies designed for people with autism: What do users want? In *10th International ACM SIGACCESS conference on computers and accessibility*, 3–8.

Riedl, M.; Saretto, C. J.; and Young, R. M. 2003. Managing interaction between users and agents in a multi-agent storytelling environment. In *Proceedings of the second international joint conference on Autonomous agents and multiagent systems*, AAMAS '03, 741–748. New York: ACM.

Riedl, M. O.; Thue, D.; and Bulitko, V. 2011. Game AI as Storytelling. *Artificial Intelligence for Computer Games*.

Sloman, A. 1998. Damasio, Descartes, Alarms and Meta-management. In *In Proceedings International Conference on Systems, Man, and Cybernetics (SMC98)*, 2652–7. IEEE.

Tartaro, A., and Cassell, J. 2008. Playing with virtual peers: Bootstrapping contingent discourse in children with autism. In *Proc. of the International Conference of the Learning Sciences*, 382–389.

Weld, D. S. 1994. An Introduction to Least Commitment Planning. *AI Magazine* 15(4):27–61.

Wooldridge, M., and Jennings, N. R. 1995. Intelligent Agents: Theory and Practice. *Knowledge Engineering Review* 10(2):115–152.

Young, R. M. 1999. Notes on the Use of Plan Structures in the Creation of Interactive Plot. In *AAAI Fall Symposium on Narrative Intelligence*. AAAI Press, Menlo Park.

Zilberstein, S. 1996. Using anytime algorithms in intelligent systems. *AI Magazine* 17(3):73–83.