Informing the design of a virtual environment to support learning in children.

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ABSTRACT

This paper describes how different kinds of research activities (theory building and application, exploratory and experimental studies, prototyping, user testing) are instrumental in informing the design of virtual environments. We show how general user-centred design methods can be used when tackling specific issues concerned with the properties of virtual environments. To illustrate our approach we describe how we have designed a virtual theatre for young children to support learning through playing. We end with a general discussion of the core issues that need to be considered when designing virtual environments.

1. Introduction

One of the main attractions of virtual environments is that they can provide opportunities for new kinds of experience, enabling users to interact with objects and navigate in 3D space in ways not possible in the physical world (e.g. flying a magic carpet through a fantasy world). Many claims have been made about the ‘added value’ that can be gained from interacting with these kinds of virtual representations, such as easier learning, better understanding and training, more engagement and more pleasure (Psotka, 1995; Winn, 1993, Rheingold, 1991). To explain these benefits it has been suggested that one of the key properties of VEs is their ability to captivate: for example, Bricken and Byrne (1993) suggest that immersion in 3D environments is highly motivating, inducing users to spend more time on a given activity. Similarly, Allison et al (1997) found that in their virtual gorilla project users were highly engaged and very much enjoyed the experience (the users adopt the role of a gorilla in a virtual zoo, navigating the environment and watching other virtual gorillas respond to them).

From an explicitly pedagogical perspective, Wickens (1992) has proposed that virtual environments encourage people to be more active in the way they interact with external representations, through having to continuously choose their
position and viewing perspective when moving through the virtual environment. In so doing, he suggests that learning and retention of information can be increased. Having access to multiple representations through multimodal interaction is also assumed to aid learning of abstract concepts (Dede et al, 1996). These explanations, however, offer little insight into the ways that users do or should interact with the technology. Our current knowledge about the nature of navigation and user interaction with VEs is still very limited (e.g. Stanney, 1995; Scaife and Rogers, 1996; Poupyrev et al, 1998). Consequently, there exists little guidance on what methods to use to design VEs to enable the putative benefits to materialise – such as better learning, more engagement and enhanced understanding. Moreover, given the various interacting factors that need to be taken into account (e.g. the activity being supported, the experience and characteristics of the user group, the appropriateness of the interaction styles) it is difficult to know how best to carry out an informed design process for VE (Salzman et al, 1999). Rather than these issues, much of the research focus has been on investigating technical and ergonomic aspects of developing virtual reality applications, such as the usability of various input devices (Lindeman et al, 1999; Zhai, 1998) and the development of effective techniques for realtime rendering of 3D graphics (e.g. Li and Lau, 1999).

One obvious approach is to adopt existing HCI and interaction design methods, such as participatory design, user-centred design and various usability life cycle approaches. Many of the requirements for developing interactive systems, when using more established software environments (e.g. hypermedia, multimedia) are highly relevant for designing virtual environments. For example, the need to do early evaluation and prototyping are now universally accepted as de rigueur for any kind of system building and software design. However, these are quite general methods that need to be tailored to the particular demands of the user group and application domain being developed. Further, and crucial in the present context, they also need to be combined with more specific questions to do with the particular properties of the media being implemented. For example, when developing multimedia environments a specific concern is how best to select and integrate the various media to match different activities to best effect, e.g. contexts appropriate to the use of sound, text or graphics. For virtual environments, a core specific concern is determining an effective way of representing and visualising objects, scenes and data at the interface such that they can support the interactions, activities and navigation that the user should be able to control and do for themselves. It includes resolving particular interface issues to do with the level of realism and immersion that is appropriate for the concepts being represented and the tasks being supported. Another important concern is deciding upon, and then knowing how to, integrate the VE with other forms of representation (e.g. interaction modes such as menu options, speech recognition, gesture recognition) that are going to be used in the application being built.
There are, therefore, a number of concerns specific to the design of VEIs that need to be taken into account when following a general design methodology. In this regard we have been evolving a user-centred design approach for developing interactive software environments that combines general methods with specific concerns, aimed at supporting users in their understanding and learning of a given domain. Initially, we developed a general framework which was intended to be used to inform the early stages of selecting, designing and combining various representational formats (e.g. diagrams, animations, multimedia) based on our theory of external cognition (Scaife and Rogers, 1996). Using this framework, we then produced a more detailed methodology specifically for guiding the development of educational multimedia software (Rogers et al, 1999). In the last two years we have adapted and extended the methodology to inform the design of virtual environments to support various learning activities.

The purpose of this paper is to outline how different kinds of research activities (theory building and application, exploratory and experimental studies, prototyping, user testing) are instrumental in informing the design of VEIs – especially in helping to attain their goals. In particular, we shall demonstrate how to adapt and combine well known user-centred design methods to cater for the demands of designing virtual environments to support learning. Whilst there has been much written about the potential of VE for supporting learning (e.g. Wickens and Baker, 1995) and numerous virtual learning environments built to demonstrate this, there has been little written about the design rationale behind their development. It is often difficult to glean why and how design decisions were made about specific VE concerns or indeed what dilemmas and conflicts had to be resolved. Furthermore, the use of theory in informing the design decisions appears to have been scant and when presented has tended to be somewhat tokenistic or ad hoc, for example relying largely on the one or two ‘big’ ideas from constructivism (e.g. the value of hands-on and exploratory learning) to explain why interacting with virtual representations is important for learning.

To begin, we will give an abbreviated overview of our approach to designing virtual environments. This involves a number of stages, which are carried out in a progressive manner. Each stage involves a number of activities which are performed in parallel; the various outcomes are used together to inform the next stage. The philosophy for the approach arises from an appreciation of the ways that designers work and the problems they face, derived from many interactions with them in research and development projects. Following this framework overview we shall then illustrate its possible use by showing how it is being used to inform and guide the design of a specific VE application – the creation of a virtual theatre for young children to support learning through playing. In this project our aim was to provide young children with a means of extending their existing repertoire of story telling by providing them with a new set of tools that they could use to create, edit, direct and act out plays in a virtual, imaginary setting.
Following our presentation of the virtual theatre case study we discuss at a more general level specific issues and dilemmas involved in the process of designing VEs. We have opted for this approach, rather than adopting the more conventional procedure of proposing guidelines, because we have found it to be more useful for designers. Our experience with working with designers suggests they prefer a more generative approach, especially when confronted with trade-offs, conflicts and problems. Learning through case studies, war stories, hands-on examples and analogy is proving to be a more useful way of informing designers of the issues and helping them steer through the complex process of design (e.g. see Winograd, 1996). In these respects one major role of the researcher can then be glossed as abstracting from particular examples to provide more general principles about design practice, ranging from understanding design choices to improving communication between design team members (e.g. Green, 1990; Hughes, Randall & Shapiro, 1992; Scaife, Curtis & Hill, 1994). In the discussion, we will refer back to the dilemmas and issues we came across in our project and suggest how to describe them in a sufficiently abstract way to reveal their generalisability to other VE design applications.

2. The design framework

2.1 STAGE 1: OPERATIONALISING HIGH LEVEL REQUIREMENTS:

Firstly, we consider it important to know at the outset what and why we are building. This enables us to have a clear picture of the problem space before committing ourselves to a particular design solution. As is well known in user-centred design, developing software, like VEs, is a process that is highly 'viscous' (Green, 1989) – in the sense that it is very time-consuming, laborious and costly to make changes to a design once the coding begins. In contrast, it is much less viscous to find out and understand the nature of the problem space before starting any prototyping.

This preliminary stage of the design process is essentially concerned with operationalising the high level requirements for the system in terms of:

- the nature of the problem space
- the claims about the putative benefits of using a particular kind of technology (in this case VE) and the assumptions behind them
- an analysis whereby relevant theory to support the above is operationalised
- discovering what is already out there with respect to what is being developed and what are the pertinent unresolved research issues and dilemmas
- identifying the user group and existing problems they have with the domain
- considering which forms of representation (e.g. desktop/immersive, animation/interactive, 2D/3D), interaction and control mechanisms (e.g. embedded versus separate, external menus) and I/O devices might be most appropriate and how to combine them
FIVE STAGE APPROACH

1 OPERATIONALISE HIGH LEVEL REQUIREMENTS
   theory  technological possibilities  existing research

2 SPECIFIC RESEARCH QUESTIONS
   exploratory studies  Informant Design
   design implications

3 PROTOTYPE & VE DESIGN
   mid-tech prototypes
   user testing
   technology selection
   further design implications

4 CONCEPTUAL MODEL FOR VE

5 IMPLEMENTATION & EVALUATION OF FINAL DESIGN

Figure 1 Framework for the complete design methodology
The outcome here is a first identification of the scope of the problem space and a set of ideas about which problems are to be addressed in what way. While this phase is time-consuming we believe it enables us to be better informed about the benefits and ‘added value’ of using a VE for the activity/domain space being designed for.

2.2 STAGE 2: EXPLORATORY STUDIES AND INFORMANT DESIGN

The second phase involves looking at current and possible future practices in the domain space delimited in the first phase. This involves two components:

(I) we ask a number of ‘informants’ (e.g. children, teacher, parents) to give us their views about the problem space. Each will have a different perspective and it is important to be aware of these differences and how they complement or conflict (Scaife et al., 1997).
(ii) we carry out a number of exploratory studies, where we observe users carrying out activities in their current environment. This allows use to establish a baseline by which the proposed solution can be compared with and how existing media and artefacts are used.

The timing and extent of the contributions from these two activities will obviously vary with the particular project but we can say something of their contributions to the shape of the design. The informants play a crucial role in identifying for us parameters that we otherwise would have no awareness of. For example, being able to envisage the situated use of the product from both their own and other user perspectives can reveal socially-based norms which are beyond the scope of other analytic techniques (e.g. cognitive walkthroughs). A good example here is of revealing gender-based preferences for particular visualisations.

The outcome here is to identify constraints on the range of possible design ideas by identifying needs, preferences and existing practices. It differs from more elaborate co-design regimes (e.g. participatory design) in that we use the informants as a source of ideas and validation, rather than as co-equal designers.

2.3 STAGE 3: PROTOTYPING AND USER TESTING

The third stage involves starting the design of the VE application. Based on the outcomes of stages 1 and 2 various designs are ‘fleshed out’ through building preliminary prototypes. These are:
• low-tech (e.g. paper mock-up) and mid-tech (first software) prototypes to explore particular functions and possibilities
• scenarios, storyboards and scripts and sketches of particular interface components and interaction styles.

Having built the prototypes it is important to do some preliminary user testing to validate assumptions and resolve problems. In so doing, proof of concept can be put to the test. As this is essentially a validation and clarification phase the
numbers of participants taking part in the studies does not have to be large. The aim is to get an idea of the range of user responses rather than to find that a large numbers of users will interact or navigate in the same way. Hence qualitative analysis is preferred, often using video analysis of user performance.

The outcome from this phase are a set of specific design implications, which are intended to inform directly the conceptual model for the application. By this we mean that the work to date should have been sufficient to allow major decisions to be made about the system to be built, e.g. how realistic the VE should be, what kinds of control and interaction mechanisms to use.

2.4 STAGE 4: SPECIFYING THE CONCEPTUAL MODEL
Based on the design implications of the preceding phases a conceptual model is then outlined. This is essentially a set of specifications for the functionality, look and feel of the VE and the range of activities to be supported in relation to the goals of the system. Following on from stage 3, the level of detail should be sufficient that it can be used as a vehicle for discussion and potential ‘hand-over’ to the programmers. It is worth emphasising that the clear identification of goals is crucial here. No matter how fine-grained the model may be there will still be emergent design problems and giving the designers/programmers a clear rationale will help them to make appropriate choices.

2.5 STAGE 5: IMPLEMENTATION AND EVALUATION
This stage involves implementing the system in the chosen VE toolkit¹ and evaluating the system at various stages as it is iterated, with respect to the objectives/goals of the VE. In our research we have identified at the outset specific learning goals which are operationalised as a set of criteria for user evaluation.

The complete methodology is illustrated in Figure 1, showing the various activities and outcomes for the various stages.

3. The Case Study: the Virtual Theatre

This section exemplifies how we used the design framework sketched above to inform the development of a virtual theatre as part of a research-based project called PUPPET. The project is part of the European Union’s i3 ESE (Experimental School Environments) research programme, which seeks to develop innovative learning tools for children aged between 4-8 years – a target user group who are at the crucial developmental stage of achieving literacy and who, until recently, have not received much attention in terms of innovative IT to support their learning. The PUPPET team is multidisciplinary, comprising computer scientists from Aalborg University, Denmark who are programming the

¹ It is assumed that that decisions about which programming environment to use will have been made by the programmers – in consultation with the designers. In our case a combination of Performer, C and Java were decided upon.
virtual environment, dramaturgists from Aarhus, who are providing models and theory from drama education and practice, and AI researchers at DFKI, Germany who are developing the agent architecture for the VE.

The basic rationale for the PUPPET project, was as follows. Young children are highly imaginative when playing and telling stories in the every day world. We wanted to know how we could use the computer’s capacity for creating new (virtual) environments to extend their imagination even further. In particular we wanted to develop a virtual 3D theatre that would allow children to act out, script, edit and direct their own plays in ways not possible with physical theatres at this age.

Below we provide more detail on the ways in which we made decisions about precisely how we went about informing the design of the virtual theatre to enable this form of learning to happen. To achieve our aims, we adopted an interdisciplinary user-centred design approach, informing the design of the virtual theatre and its use from a range of inputs, including: exploratory studies, software prototyping, user testing, developmental and drama theory, external cognition framework and informant design. In the next section, we describe the design of the first virtual theatre, for 4-6 year olds, through the steps of the framework, with only the final evaluation remaining to be done. We are, therefore, able to illustrate a complete cycle.

3.1 STAGE 1: OPERATIONALISING HIGH LEVEL REQUIREMENTS:
This is the phase that asks what and why we are building – a delimitation of the problem space before committing ourselves to a particular design solution. The first, crucial step for us was to identify, a priori, the potential value of VEs for the children. We did this on the basis of three, inter-related considerations:
• how the available technology could provide new possibilities for interaction consistent with our theoretical interpretation which is
• a view on how representations in general work as a support for learning based on our theoretical analysis of external cognition interpreted in the light of
• what the available research literature, and our own experience, suggested about the capabilities and potential of the user group in question

3.1.1 Technological possibilities: virtual and the physical worlds
As we watch young children play we are usually struck by the fact that they are immersed in the activity, finding it highly motivating. But consider the differences between the following examples. In the first the child is making a play using two hand puppets, in the second the child is playing through interacting with a computer-based game such as Super Mario. In both situations the child is likely to be totally engrossed but there are significant differences between the two in terms of social, cognitive and affective experiences. The puppet play occurs in the physical world and involves lots of imagination, where the child improvises by
acting out different roles, constructing storylines and setting up dialogues between the puppets. By contrast, the computer game takes place in a virtual world and involves a highly focused, complex problem-solving activity, requiring high levels of sensory-motor skill but may require little imagination from the child.

The latter situation would seem true for the vast majority of current software and educational games for young children. Plotlines, characters, etc., are already provided for them in the software. Typically, the child is required to reach an end goal, such as searching for treasure with little, if any, scope for using the imagination and improvising, for example, who the characters should be or what they should look like or do. Even in the relatively new arena of avatar and agent-based virtual worlds, much of the behaviour, emotions and reactions are predetermined by the system. This suggests, therefore, that there is a big difference between how children play in their everyday life and what they are able to do with the kinds of virtual playing currently supported by computer-based technology. It led us to ask: ‘how can we develop computer-based systems that can better support and extend the improvised kinds of play that occurs in the everyday world?’

One of our main rationales for using a theatre metaphor was, therefore, that we believed that this kind of setting would allow children to switch between various kinds of creative and imaginative activities, enabling them to, ‘suspend disbelief’ from multiple perspectives and reflect upon this process (see also Laurel, 1992). Dramatic symbolic play has a special role in enhancing narrative and imaginative skills by “playing out various roles and trying out different voices and situations. Children can polish their abilities and transform external experience into small scale, controllable forms, developing their means of storytelling and their narrative thought” (Singer, 1994). With this in mind, we believed that a virtual theatre would enable children to exercise both imagination and creativity during playing. There is much scope for extending theatre-based activities, e.g. acting, scripting, editing and directing, at the interface, through allowing the children to create and modify plots and build composite characters in terms of personality, emotions, behaviours, actions, interactions with others. We were concerned to develop the child’s sense of narrative. The term ‘narrative’ has had many different definitions but we follow Bruner (e.g. 1986, 1990) who identified four elements of narrative capacity: (1) a sense of human agency and purposeful action; (2) a sense of sequential and consequential order; (3) a sense of canonicality, or the progression of a normal or appropriate story; and (4) a sense of a narrator's point of view. Our first step, therefore, was to determine what kinds of computational structures and interactivities might encourage the competences Bruner identifies as underlying the production of rich stories and plays in the development of narrative skills. If PUPPET is to provide the right kind of virtual play environment we needed to ensure that it had a viable theoretical justification for making such choices.
3.1.2 The theory

One of our claims about the value of the virtual setting, over and above a physical one, is that it can provide a more extensive range of support for children to be creative – and in ways not possible in the physical world. A major difference between the environments is that, in physical play, the activities are ephemeral and children cannot step back from them to change what they have done without major mnemonics effort. Following our theory of external cognition (Scaife and Rogers, 1996) we argue that, by contrast, a virtual theatre can be structured to allow reflection and consequent understanding of the different roles involved in story development and enactment. This is achievable by having the theatre allow and manage external representations of the story elements and supplying tools for the children to create, edit and produce the story. In particular, various kinds of external representations can be used at the interface to help children act out, structure and edit their story or play. These include the use of avatars, scripting tools (e.g. interactive storyboards, dynamic diagrams, cascading menus of options for building up composite characters, such as personality traits, emotions) and icons to represent sequences of action. Whilst a variety of scaffolding structures are available in the physical world (e.g. teacher, peers, props, paper versions) the virtual theatre offers the potential for many additional kinds of external support.

Thus a main benefit of such externalisation is that it can decrease cognitive effort in carrying out activities, enabling children to focus on the structure of a story rather than on small details – which necessarily happens when they have no external support. Our analysis led us to consider that we needed to provide a combination of tools. Some were ones that children could readily identify with, that were analogous to everyday play. Others would be innovative tools that could extend current means of how they played and learned. An example of the former is a painting tool that allows the user to ‘colour in’ features of virtual characters (e.g. clothing). An example of the latter is a magic wand which, when struck against a virtual object, morphs it into something else or causes it to become animated. However, before setting out to design new tools we first needed to consider the lessons that existing research had shown.

3.1.3 The research background

In the present context there are two major areas of current research which are relevant to our goal of constructing a virtual theatre. The first area concerns the increasing number of computer-based systems that have been built to help support learning through playing. One approach has been to configure various physical toys, e.g. LEGO bricks, balls and beads, so that children can change their behaviour (e.g. move them around) by programming them at a computer interface (Resnick et al, 1998). Another approach has been to encourage learning through playing by embedding cuddly toys with computer systems. Recently, commercial products like ActiMates have been designed to try to encourage pretend play in young children. For example, Barney attempts to initiate play in children, through using speech and movement (Strommen, 1998).
The toys are programmed to react to the child and make comments whilst watching TV together or working together on a computer-based task.

Stuffed toys have also been used in a mediating role to specifically improve story-telling skills in young children. For example, ‘The Things That Think’ group at the MIT Media Lab have been building a range of software tools, in the guise of stuffed toys, that try to encourage children to write stories (e.g. Glos and Cassell, 1997; Umaschi, 1997). One example is SAGE (Storytelling Agent Generation Environment), which is a conversational, personal storytelling system where the storyteller agent is embodied in a stuffed rabbit, that takes different personalities according to the hat it wears, e.g. as Rabbi or Taoist priest. Another approach to encouraging story-telling is the StoryMat, which records and recalls children’s stories in combination with the movements they make with their toys on a physical play mat. The rationale behind this design is that hearing and seeing one’s own and other children’s stories being played back via the StoryMat encourages children to tell more stories (Ryokai and Cassell, 1999).

Another relevant area where this has been some interesting research is the interaction with story characters in virtual worlds. For example, the Synthetic Characters group at MIT have been developing ‘sympathetic’ interfaces, where the user changes the behaviour and attributes of virtual characters in a virtual scene through manipulating a wireless connected physical soft toy (Johnson et al, 1999). Here the emphasis is very much on getting the child to control a character (e.g. a chicken) which changes its behaviour accordingly but also reacts to other events happening in the virtual world (e.g. a racoon trying to steal its eggs). In this context, the activity to be accomplished by the child is essentially a problem-solving game.

Most specifically, in terms of how to develop characters in virtual worlds, there are projects, such as Intellimedia at North Carolina State University, which have been investigating what properties agents should have to be efficient in teaching children from kindergarten to teenage in tasks such as learning plant names or geography. Their studies show that animated agents need to be realistic in terms such as their behaviour in pointing out objects and in their capacity for emotional understanding – a key ingredient in motivating the child (e.g. Lester et al, 1999). Stanford’s ‘Improv Puppets’ is another system where synthetic agents, embodied as animated characters, perform simple vignettes in response to abstract directions from the child and the system (e.g. Hayes-Roth and van Gent, 1997).

A key question that arose from this survey of the literature was what role the child should play in relation to the physical toys or virtual characters and vice versa. As we have seen, sometimes the child is meant to relate to the toy in second person, talking to and playing with it. At other times the child takes the role of third person, controlling a character in a virtual world or telling a story, whilst in other situations the child is given the opportunity to experience a narrative in first person, by interacting with or navigating through a virtual world. An example of
the latter is Disney Imagineering Group’s high-fidelity VR attraction, that has been designed to enable visitors to fly a magic carpet through a virtual world based on the film of Aladdin (Pausch et al, 1996). In these kinds of worlds, the immersive, first person perspective afforded by VR is claimed to “create the opportunity for emotional impact through empathy, discovery and personal choice” (Pearce, 1997).

3.1.4 Outcome of stage 1
The results of the first stage were the identification of what a virtual theatre could offer, on what basis it could support play and of key research issues such as viewpoint and behavioural characteristics of actors. On this basis the following design issues and high level requirements, were highlighted as ones for investigation in the second stage of exploratory studies. Each issue is followed by the appropriate empirical question for stage 2.

(i) Role switching
Design: How many roles should the child be allowed to take on? How do we support the switching between 1st person acting out and 3rd person scripting in terms of making the mode distinction obvious to the child?
Empirical: How many roles can the child take on? How do children handle the switching between 1st person acting out and 3rd person? Issue addressed in exploratory studies 1 and 2.

(ii) Realism
Design: What kinds of realism to provide at the interface? How believable should the characters appearance and behaviour be? What kinds of representations, in the form of props, animations, etc. should be used?
Empirical: How much realism do children need/provide in their everyday play? What kinds of props do they/can they use? Issue addressed in exploratory studies 2 and 3 and also in the informant design sessions.

(iii) Interactivity and externalisation
Design: What kinds of interactivities and external representations to include at the interface to support the child in constructing their plays? For example, how much of the behaviour, emotions and other attributes of characters should the user decide and how much should the system determine?
Empirical: How complex is character construction in children’s play? How far do they manage dramatic devices such as character switching or floor changes in speaker? Issue addressed in exploratory study 3.

(vi) Narrative
Design: What kind of prior narrative structure to provide in order to promote greater narrative expression by the children themselves? How much of it should already be apparent and how much freedom should the children be given to develop it, themselves?
Empirical: What is the effect on story production with different settings? For example the children could be given either a theme (e.g. a story about going to the shops) or a structured, beginning-middle-end plot to produce. The former allows for more imaginative play while the latter frees the child to focus on detailed production. Issue addressed in all studies.

3.2 STAGE 2: EXPLORATORY STUDIES AND INFORMANT DESIGN

To answer the above questions, it was imperative to begin with a baseline, explicating what children currently do when playing in different settings. Whilst we were able to abstract a number of findings from the literature about narrative, role switching and realism, it also became very apparent to us that there was a paucity of research on interactivity and externalisation. In particular, little attention had been paid to how different kinds of externalisation can support children’s development of narrative and their meta-level understanding of the underlying structure. To this end, we carried out a series of exploratory studies, investigating the mediating role of different conditions on children’s ability to create stories. The studies were videoed and the structure of the stories, use of props, incidents and breakdowns in storylines (e.g. distractions) analysed. We also asked children, teachers and parents about their preferences, views and ideas for how to extend existing forms of play in a virtual environment. The rationale and main findings of the studies and informant design sessions are briefly summarised below. The children whose results are described for Stage 3.2 were 4-6 years old and took part in the study in school settings, in their usual classrooms. They were selected by their teacher as representative of the abilities of the age group concerned and all had some experience of computer use.

3.2.1 Exploratory Study 1 – Investigating role switching and forms of narrative generated in existing forms of spontaneous play

Method: Five pairs of 4-5 year olds were asked to make a play with a range of props and hand puppets that were provided in either a lab or school setting. In some cases a toy stage was provided and other children acted as audience. The theme was left to the children. Sessions typically lasted 30 to 45 minutes.

Rationale: To investigate the ability of children to construct and elaborate stories using puppets and how they switched roles

Main Findings:
- children directly identified with characters represented by the puppets, and acted out first person dialogues between them (e.g. mouse trying to find some food and a rabbit helping out). Readily switched between the two characters played on each hand by changing voices when it was that character’s say.
- stories were short episodes, which were disjointed; children used ad-hoc narrative devices, such as ‘and then’, to move between action sequences.
3.2.2 Exploratory Study 2 – Investigating the role of story settings and props in play

Method: A storyline was given to five groups of two or three 4-6 year old children, which was set in a typical farmyard. They were given different conditions, in which the richness of props and setting was varied. In the ‘rich’ condition a range of toy animals, fences, gates, model buildings and other props were provided. In the ‘minimalist’ condition, a background, one cardboard box and a finger puppet were provided. The children were told the beginning of a story and asked to complete it. Briefly this was that there had been a big storm and all the animals had escaped from their homes. They were asked to act out, using the props, what happened. Sessions typically lasted 30 to 40 minutes.

Rationale: To explore children’s narrative when manipulating different configurations of physical toys with a background scene and when given a partial storyline structure and problem to solve. Also, we wished to determine what roles children took on.

Main Findings:
• less identification with characters than with in previous study - narrative was told through acting out rather than verbal commentary and children used 3rd person voice. Little evidence of actually switching between 1st and 3rd person
• prompts/scaffolding from adult helper were needed to perpetuate the story-telling
• props were used in an imaginative way, changing smoothly from one identity to the next
• in the rich condition the children were easily distracted by props, suggesting new bits of story which did not follow
• in the minimalist condition children identified with the farmer character much more.

3.2.3 Exploratory Study 3 – Investigating symbolic story construction

Method: Four children, aged 5-6 years, were asked to construct a story using picture cards depicting various farmyard characters. The theme was stated as being ‘about animals and people on a farm’ but no more detail was provided. They could choose cards from a large set on the table before them. Sessions typically lasted 15 to 20 minutes.

Rationale: To determine whether external representations, in the form of static iconic pictures, would assist children in sustaining their storylines

Main findings:
• children initially gave contextual descriptions of individual cards with no attempt to make connections between them, constructing the storyline as a series of serendipitous links between adjacent cards
• after a while the selection of new cards induced the children to start to make longer connected thematic sequences in their stories, incorporating several cards into a sequence.
3.2.4 Informant design sessions

In addition to the exploratory studies we also used the second method appropriate to this stage, that of asking children, parents and teachers about play. The input from these sessions complements the findings from the earlier studies in that it provides an interpretation of what currently works and doesn't and what might or might not work from the perspective of different kinds of users rather than just ourselves, as researchers. Moreover, it is an opportunity for us to discover unexpected aspects and things we don’t know rather than confirm or contradict what we thought we knew (as happens when carrying our empirical testing).

The children, being very young, could not be asked very much about their views on a possible virtual theatre. However some nine pairs from a class of 5-6 year-olds were observed using various CD-ROMs in the classroom, almost all in the form of educational adventure games, over two class sessions – forty minutes each. Some of these utilise an avatar-like character, such as a duck walking through a farmyard, and we were able to ask questions about the children’s abilities to understand the perspective changes and field of view of the character. We were also able to determine some of their preferences for forms of interaction with virtual characters. In brief they seemed to have no trouble switching between character viewpoints.

We also spent time with classroom teachers and parents to find out information about the young child’s ability to take part in dramatic activities. This is essential because the cultural milieu of the child is changing rapidly. For example few of the children in our local schools have had much experience with conventional ‘fairy stories’, such as Jack and the Beanstalk, which has major implications for
the kind of genre\textsuperscript{2} knowledge that they might bring to a virtual theatre and, consequently, of what we need to make explicit in such a system.

3.2.5 Outcome of stage 2 and design implications

The studies and informant design sessions were very revealing and highlighted to us a number of design issues. A general finding was that the children were playing with the animals and props in a 'here and now' fashion and had some difficulty in planning and constructing a storyline with a canonical structure (e.g. beginning, middle, end) or even long connected sequences. It was interesting for us to find, therefore, an effect of increasing the abstractness of the external support: children were able to sustain and develop more coherent stories with abstract and schematic representations (e.g. plain box, picture cards) compared with a full realistic setting, replete with characters and toys. One reason for this is that, with more abstract/schematic representations, children are not so easily distracted but better able to plan ahead. Thus, where optimal conditions for planning are available, i.e. with good external representational support, the children can readily develop connected themes in their stories.

In Phase 1 we identified a number of high level requirements, relating back to our questions identified in phase 1. We also identified a number of other interrelated design concerns. This led us to propose the following design implications:

- **Narrative** – children of this age need to be able to implement some of their own ideas to maintain interest and motivation but not at the top-level of creating an entire story from scratch. An example of appropriate freedom is being allowed to create their own characters and actions within an existing plot structure.
- **Interactivity and externalisation** – external representations should be provided that constrain the way the children manage the sequences within stories to help them plan themes and events. Minimally symbolic forms, such as the cards, provide stimuli that the children can then elaborate and embellish.
- **Realism** – children readily identify with simple and cartoon-like characters (as used in the picture cards). By limiting the degree of realism it allows the child to use their imagination to conjure up characteristics of the agents and avatars.
- **Role switching** – physical toys which are manipulated by the child promote 3\textsuperscript{rd} person narratives whilst puppets which are worn by the child promote 1\textsuperscript{st} person acting out story telling. There was little evidence that they spontaneously switched between different roles. This is something we want to promote in the VE and, therefore, suggests that different kinds of interaction with characters in a VE is necessary to allow the child to be able to switch between different viewpoints.
- **Mode switching** - children can easily manage both acting and editing but the system should make the change in mode very clear to the user.

\textsuperscript{2} By ‘genre’ we mean here an understanding of a canonical story structure that informs the child about likely developments in plot, roles of characters and so on.
3.3 STAGE 3: SOFTWARE PROTOTYPING, USER TESTING AND VE DESIGN

The third stage involves starting the design of the virtual theatre. We began by developing a number of partially-functioning prototypes (mid-tech) which simulated a 3D environment using either Java or Director. The rationale for developing these mid-techs was to allow us to validate various proofs of concept in a very short time. The prototypes each took only a few days to knock up and were able to be rapidly amended or extended to test out further aspects that arose in the first stage of user testing. Moreover, many of our high level concerns to do with creating, editing and directing a virtual play (e.g. whether the child understood how to make up a composite character using a palette of various icon options) did not need to be tested out in a VE environment since we assumed that many of these actions were to be carried out using separate 2D interaction mechanisms.

Our primary concern at this stage, therefore, was to investigate how children reacted to different kinds of interactivity and interfaces. We wanted firstly, to get a sense of how children understood the syntax and semantics of manipulating screen characters and secondly, to see if they enjoyed doing this. Since these children are largely pre-literate we had to ensure that we could provide visual surrogates for the functions that text and other symbols are usually used to represent. Seven children, 4 and 5 years old, were the users for the prototype testing with sessions for each prototype typically taking 30-40 minutes. They were brought individually into the lab with an accompanying parent and sat next to the computer with the aid of an adult helper.

3.3.1 Mid-tech prototyping and user testing

The child was invited to explore the interface and then asked to perform a number of tasks. One of the first prototypes developed was a simple farmyard scenario, with interactive characters. A pig and a cow could be moved around, using drag and drop interactivity. The basic task was for the child to get the animals home, across a river using a bridge. We were interested in examining a particular form of on-screen externalisation, where, when the animals were dragged, they left a trail of footprints showing where the animal had been. This kind of interactivity is not possible using physical toys and is potentially useful in editing a story where the child needs to remember animal movements. In one condition, we set the children a task, which was to get the animals back to their respective homes. Constraints were built in, such as not allowing the pig to go into the cowshed or animals to ford the river. Here the idea was also that the child should learn that ‘rules’ applied, such as – (i) animals can’t walk across water, (ii) they can only get across the river via the bridge, (iii) they are only allowed in their own home and not the other animal’s. The children responded with enthusiasm and showed an easy fluency in moving the animals and of understanding the rules.

Another series of prototypes were developed to investigate how children solved more complex problems by combining a syntax of actions. This resulted in a non-
verbal form of representation to accommodate our target group being unable to read. Thus we needed to think of alternatives to using words and conventional signs (e.g. +, ?) to develop a meaningful syntax for controlling and sequencing the character’s actions. Five of the same set of children as saw the previous prototype were the user group here. The farmyard scenario was used, but with a number of additional functions. Firstly, we provided a set of animal sounds which were represented on screen as abstract speech bubbles. The idea was to see how easily children found it to attach sound to the pig and the cow. Again a form of externalisation was used to indicate the action of attaching sounds. Selecting a speech bubble and then clicking on an animal resulted in the sound being made, with a copy of the bubble appearing next to the animal on the screen. Five of the same set of children as before and two new ones, saw the previous prototype were the user group here. They enjoyed the auditory-visual coupling, especially when contravening the ‘rules’ of the farmyard, by attaching cow or horse sounds to the pig and vice versa.

Having learnt how to attach sounds to the animals, we wanted the children to then learn how to change events and create dialogue between the characters. The same problem-solving activity was used, only this time made more complex: they had to get both animals home safely but with a new constraint. If the animals arrived at the bridge at the same time they would crash. To solve the problem required setting the speed of the movement of the animals to be different. Two icon buttons, depicting the animals in different stages of movement, were provided to direct the speed of each animal (slow, fast). The children needed to select an animal and then its speed and then do the same for the next animal, before finally selecting a ‘go’ button to see the outcome of their combination of animal movements. Hence, a sequence of choices were required
before the system displayed the animation of the two animal’s movements. When we presented all the buttons together in the same interface, the children found it quite confusing and difficult to grasp what they were supposed to do. However, when we presented them separately, introducing new buttons only in a serial manner, they were able to learn much more effectively the syntax that was being represented. This finding suggested to us the importance of introducing tasks and control features at the interface in a modular and step-by-step fashion.

Finally we introduced a further character into the farmyard prototype: a farmer. The farmer was designed to appear on the screen at various stages of the unfolding scenario. For example, he would appear when the two animals crashed at the bridge. Here we wanted to see how well the children would manage character construction – having the option of changing the emotion of the farmer and matching this to what he said. The child could do this by clicking on the farmer’s face. This caused a pop-up menu of facial expressions to appear (e.g. happy, angry, sad). Clicking on the farmer’s body would cause another pop-up menu to be displayed. This time a series of speech bubbles was presented, each representing different things the farmer might say (e.g. what are you silly animals doing here? Thank goodness you are here, I’ve been looking for you all over the place). The child has to choose one and match it with the facial expression. If they want to they can then go back and change the facial expression. Testing of this functionality showed that this was something that the older children (5 rather than 4) could manage, the difference being that, while the younger children understood the task, they had problems sequencing the actions.

3.3.2 Selection of I/O Devices and Interfaces
During the informing phase of the project we had many ongoing debates with our partners about technological aspects of the Virtual theatre. One major debate was about the kinds of I/O devices to select – given the age and size of our user
group. Head mounted displays, datagloves and shutterglasses\(^3\) were considered inappropriate insofar as they have not been built in small sizes (having them customized was far too expensive). Adapting adult-sized devices was also considered not practical. The problem of doing so is illustrated by Roussos et al (1999) in their VE study: for example, when they tried to adapt shutter glasses for second grade students by using glass-ties they found that the glasses kept falling off or the children took them off as they were too uncomfortable. Given these practical constraints we decided in the first instance to select a conventional output device – a computer-based screen. In terms of input devices, we explored a range of options besides the ubiquitous mouse. These included gesture and physical object recognition, the latter employing a jigsaw metaphor – where wooden cubes, covered in images, are placed by the user in a sequence that is detected by the system and played back as a story in the VE world. These attempts were based on the idea that, perhaps, children using direct physical actions, e.g. on manipulables, would benefit by not having to spend time learning to use an interface.

![Figure 5: Third mid-tech prototype](image)

Part of our discussion was based on how we were to resolve role and mode switching between enacting, editing and directing a play. We had a long discussion with our partners about feasibility of doing everything immersed in the VE world. To be able to support our learning goals, it seemed necessary for the children to be able to step back and reflect, which is difficult when fully immersed in one activity. Hence, we decided to design the 3D VE world for 'on-stage' activities (acting out, watching a play) and have a separate interaction control panel for the 'off-stage' activities (e.g. writing, editing, directing) and where the 3D VE would provide dynamic feedback of the effects of the child’s actions.

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\(^3\) Shutter glasses are devices where the eyes can be presented with stereo images by rapidly alternating the display of left-eye and right-eye images while alternately masking the right and left eye using a synchronous shutter viewer.
Ideally, a form of interaction such as the ‘pen and tablet’ metaphor, that uses a stylus and tablet (Bowman et al, 1999), seems desirable to support both forms of activity. The child could both navigate through 3D space using a stylus to traverse a symbolic map positioned on the tablet and carry out the various ‘off-stage’ actions (e.g. editing, creating characters) using a different overlay on the tablet. Owing to project constraints, however, we have opted for using a mouse, which we have found that children have no problems with.

3.3.3 Outcome of stage 3 and design implications
The clearest design implication arising from our user testing of the various mid-tech software prototypes is that the interface needs to be kept really simple and that the child needs considerable training to build up a mental model of the various elements of the system. This suggests an incremental (cf training wheels idea) type interface that is contextualised in the sub-activity that the child is currently playing in. The importance of enjoyment and surprise when children interacted with the software is also very important.

Other implications related to our main design issues include:
• realism – Providing the opportunity for the child to make bizarre and unexpected attributes is desirable (e.g. allowing the child to create green pigs and cows that make horse sounds). Crude forms of movement by avatars and agents, representing walking, running, etc., and exaggerated facial expressions representing emotions are also readily recognizable by the children (a big potential saving in design effort).
• interactivity and externalisation – different forms of analogue and novel tools were considered very effective for helping children to edit and create stories
• narrative – it is important to allow children to feel a sense of ownership of the story, for example by allowing authorship of their own composite characters, through adding sounds, dialogue and emotions

3.4 STAGE 4: SPECIFYING THE CONCEPTUAL MODEL
Based on the design implications of the preceding phases we were now at the stage of producing a conceptual model: specifications for the functionality, look and feel of the virtual theatre in relation to the goals of the system. As previously stated, the level of detail should be sufficient that it can be used as a vehicle for discussion and potential ‘hand-over’ to the programmers.

We developed our conceptual model for the virtual theatre, therefore, from the findings of the exploratory studies, user testing of the mid-tech software prototypes, informant design sessions, technical discussions with our programmers, and the operationalisation of our theoretical framework on external cognition. A core aspect of the conceptual model was that the virtual theatre should comprise a series of modules at different levels of complexity which the children work through in succession. The modules are intended to satisfy our high level requirements, by supporting different kinds of imaginative and creative activities, involving differing kinds of external support and interactivity. The
modules are also intended to be used in conjunction with an adult at successive sessions over a period of weeks, building their knowledge and stories based on previous interactions. We specified various kinds of external support (in the form of scripting tools and editing tools) as well as detailing their scope to allow the children to use their imagination in developing characters and plotlines. Below we give an abbreviated summary of the conceptual model (the original was some 20 pages long) mainly to show the mapping to the work of previous stages.

3.4.1 The modules

In module 1, in the ‘enacting mode’, the children interact with the VE directly, via navigating through and selecting objects in a virtual farmyard. They start in a farmhouse and select one of the characters presented in the house. This is activated to become their avatar. By controlling the avatar, they can explore the 3D virtual farmyard world, which is populated by appropriate objects (trees, barns etc) and animal agents. On selecting certain objects in the farmyard world or moving near to them, actions occur. The idea is to encourage the child to explore the environment to discover ‘agents’ and observe their behaviour. They also discover that agents behave in different ways, following different kinds of rules: some are simple, others are more complex. Examples include:

(i) simple actions, e.g. when move towards the pigsty a piglet pops its head out the door and starts snorting

(ii) more complex actions e.g. when select a tree a chicken appears making cock-a-doodle-doo sounds, then when select the chicken it hides behind the tree, making cackling sounds

The complexity depends on the avatar selected. For example, if the child selects the dog as its avatar the kinds of behaviour exhibited by the animals in the farmyard are different from those shown to the farmer avatar. So, if the child clicks on the wood a fox appears and ‘seeing’ the dog avatar, runs away. The child can try to chase the fox by following it with its avatar. The child has the opportunity to discover the farmyard world through acting out one/more of the characters and to learn to identify themselves with the characters through being different avatars. In so doing, they can begin to understand that the world is viewed and behaves differently from different perspectives.

In module 2, the child is asked to change the attributes of the virtual characters e.g. pig, to customize them as to how they would like them to appear in the story. After dressing their avatar they need to decide what kind of voice each character should have. In this module, the child learns how to combine physical attributes to build up their characters. This activity is done using the 2D interface.

For module 3, the objective is to get the child to understand the interaction between action and intention. The module demonstrates the consequences of changing an emotional state of one agent on the actions of another. It involves an interaction between an agent (a piglet) and an avatar (the farmer), using a simple cause-effect model. The module also introduces the difference between
an avatar that the child has control over and a semi-autonomous agent which s/he has no direct control over but which responds to changes in the emotional state of the avatar. In a typical scenario the piglet is seen running around a field and an angry farmer approaches. On seeing the farmer the piglet gets even more frightened and runs even faster. The child is asked to make the farmer persuade the piglet to return to the pigsty. To do this they need to change the farmer’s emotion so that it will change the piglet’s behaviour. This is done by combining appropriate facial expressions in a sequence, whereby each has an effect on the other character’s behaviour. In contrast with module 1, this module is designed to support the development of creativity, in terms of helping planning skills and encouraging decentring: the need to put oneself in the position of the piglet in order to understand the change in behaviour of the farmer, from angry to calm.

In subsequent modules, different kinds of activities are provided, progressively getting more open-ended, requiring increasing input from the child. These include controlling another agent’s movements through using various actions (e.g. herding), changing the behaviour of another agent through holding a dialogue with them and developing and recording spontaneous dialogue. At a later stage
children are introduced to editing tools, allowing them to change scripts they have composed. The final module requires the child putting together what they have experienced and learned in the previous modules and acting, scripting and directing a complete play, based on a skeleton structure storyline that is provided for them.

3.5 STAGE 5: IMPLEMENTATION AND EVALUATION
The conceptual model was discussed at length with our partners and various modifications made to take into account technical and system architecture concerns. The first prototype system was built, using the Performer programming environment, together with Java for the agent architecture and user interface. The virtual farmyard has been developed in a desktop VE; the child navigates through it and interacts with objects in the world currently using a simple set of mouse controls. Editing, scripting and recording of dialogue is done via the 2D GUI interface, with the aid of an adult assistant.

3.5.1 The 2D control interface
A separate 2D control interface was designed to allow the child to enter the various modules and carry out actions within them. It was designed to be displayed on a separate display and is linked to the VE theatre via a socket handler, written using a Java script. A road map metaphor is presented on the screen to convey to the child how they can move between the various modules (see Figure 6). Each icon on the road map represents a module (e.g. exploring the VE, dressing up the avatars). Selecting one of these results in the system bringing up another palette of icons to do with editing and creating actions of that module (e.g. various herding movements for moving animal agents). The look and feel of this interface was partly informed by design ideas elicited from young children about what icons, buttons and other visual elements they thought would be appropriate for representing the range of functions (e.g. recording, playback). The child-centred icons were then evaluated by other children to ensure they understood the syntax and semantics of the symbolic form of representation of actions.

3.5.2 Evaluation and further design
A series of evaluation studies are planned to test our assumptions about the benefits of the virtual theatre towards the development of a child’s social, cognitive and affective skills. In the meantime informal studies have proven to be very positive, showing how much the children enjoy using the virtual theatre.
4. Discussion

Our case study has illustrated how different kinds of research, including exploratory empirical studies, theory-review and prototyping can play an instrumental role in informing the design of a VE, helping to identify and resolve specific issues concerned with extending ways of learning. By progressing through the various stages of our methodology we were able to focus on key conceptual issues in relation to the goals of the project whilst determining the requirements for more specific interface concerns, e.g. interaction styles, forms of representation and realism, sequencing of action and interaction. As mentioned in the introduction the process is complex, requiring dealing with design dilemmas, where trade-offs have to be made.

Below we discuss some of the specific VE design issues that we came across when informing the design of the virtual theatre and which we believe that aspects of these are potentially generalisable and important to other VE applications. These are interaction control, representational format and control of narrative.
• Controlling interaction and manipulation

A central concern when designing any virtual environment is determining the optimal mode of interaction and system control for the application being built. Various control mechanisms are available, including speech input, menus of commands embedded in the environment (e.g. the virtual menu system, Bowman and Hodges, 1999) or selected from an external panel/palette. Recent innovations have also included (i) a customised virtual toolbelt that is a device which the user wears which has buttons on, and which when pressed activate a range of virtual tools that can be used in the VE and (ii) a virtual Notepad (Poupyrev et al, 1998), that allows the user to take notes, annotate documents and input text using a virtual pen whilst still immersed in the virtual environment.

Given the range of possibilities, a problem for designers is determining how best to support switching modes from acting out/experiencing a world in the first person to acting upon an object or changing a viewpoint. There is little guidance on this issue: supporting the sequencing of action changing (e.g. moving between navigating an environment, object selecting and object manipulation) is one of the least investigated areas in VE research. Moreover, there has been very little empirical research to indicate which of the various interaction techniques allow users to carry out their tasks in an optimal way (be it learning about Newton’s Laws or flying a magic carpet in an imaginary world).

Two key, interdependent concerns are the type of task and the range of actions available to achieve it:

Type of Task When flying through a dynamically updated virtual world, the user wants to be able to change gear and steer without consciously thinking about which control to move or press. Here it would seem embedded virtual control mechanisms would be most appropriate. In contrast, if the task is to understand Newton’s Laws or create a complex story (like for our PUPPET project), the learner needs to be able to reflect at a number of different levels of abstraction and so having controls that support switching between different levels of representation (e.g. symbolic, virtual) that allow the user to think and integrate knowledge seem more appropriate.

Range of actions When a VE is designed to support only a limited set of actions, e.g. change of viewpoint, various ways of navigating and selecting objects, then having a small set of hard-wired commands embedded on an input device (e.g. wand, mouse, joystick, belt) may prove to be optimal. However, when the application is designed to support a wider range of actions, it becomes much more difficult to maintain the mappings between physical control and virtual command in a coherent and consistent way. The problem, instead, becomes one of determining how to configure and map a much larger set of possible actions onto a limited set of hard-wired controls. A way round this design dilemma is to introduce virtual representations of the controls in the form of icons, sliders and other widgets that are placed on palettes, menus, strips. etc., which the user
selects, using either a stylus, mouse or keyboard. In doing so, however, it requires the user to switch from being first person immersed in the virtual environment to being more third person, acting upon symbolic objects. For desktop VEs this is relatively easy to achieve. In contrast, it is much more cumbersome and disruptive for the user to have to keep taking off their glasses/helmet to use the control panel and then put them back on again to enter back into virtual environment.

The problem of trying to fit all possible actions onto a small set of controls is illustrated in the ambitious NICE project (Roussos et al, 1999), which was designed to teach children ecological concepts by enabling them to construct and cultivate a virtual garden. A range of activities were proposed, which were realised through mapping them onto a single joystick wand that had three buttons. These included growing activities (e.g. planting seeds, watering seeds, picking plants), moving actions (e.g. leaping in the air, climbing over objects) and controlling environmental conditions (e.g. making it rainy by pulling virtual rain clouds, or sunny by through pulling a virtual sun). Whilst a joystick’s buttons may readily afford selecting, dragging and dropping, it appeared more difficult for the children to carry out the higher level actions that were mapped onto these basic functions. For example, as part of an informal evaluation it was discovered that the children found it very difficult to carry out the range of gardening tasks using the wand. One task set for them – to place vegetables in a certain configuration according to a plan simply proved to be too difficult.

For desktop VE applications, our experience suggests it maybe easier to switch between immersion/experience mode and command modes through using a corresponding control panel and display. In our virtual theatre we decided to have a separate 2D control interface to enable the child to enter the various modules and carry out the editing and directing actions within them. In so doing, it also emphasizes the distinction between switching roles which we consider important for this kind of learning. Similarly, in a follow-up study of the NICE project, new prototypes have now been built that include 2D interfaces, comprising icon options to represent the higher level gardening actions (Roussos et al, 1999). By clicking and dragging icons on a 2D palette, the user can manipulate the garden model and the underlying system responds immediately, such as plants growing, in the corresponding 3D VE.

• Determining the form of representation
In our project we were constantly having to make decisions about the ways in which to represent the form and functions embodied in the system. There were a number of different areas in which this arose.

(i) role switching
One of the benefits of VE technology is that it allows the user to switch between multiple roles and hence viewpoints. In our project we sought to exploit this capability to match our learning goals – which for high level activities, e.g. acting,
directing and editing meant allowing the child to move between them and to be able to reflect upon the differences between the roles. For lower levels of activity, e.g. attaching sounds, dialogue and emotions, we wanted them to be able to switch between characters and to take on different roles. This was made realisable by allowing them to select different avatars (e.g. farmer, dog) at different stages of the play – enabling them to see and think about the ongoing action from different perspectives.

(ii) level of realism of scenes, characters and activities
Our exploratory studies and mid-tech prototypes indicated that it is not important to have high fidelity realism of scenes, characters or movement for these kinds of learning applications. The child is able to use their imagination to construct for themselves what is happening from minimalist animations – in the way cartoonists do in animated films. If anything simple and more abstract representations appear most suited. Also by keeping the VE uncluttered it allows the child to focus more on the main activity – such as how the characters are acting and interacting with each other – rather than get sidetracked by wanting to say, change the colour of the petals on the flowers.

(iii) kinds of tools and externalisation
We suggest that providing both physical and virtual tools that have analogue counterparts in the real world (e.g. wand, belt, stick, palette) is effective. A key design concern is determining what else to provide when manipulating these, such as how much ‘magic’ functionality to provide. For example, a virtual wand should be able to trigger novel events not possible in the physical world, such as transforming objects and morphing (e.g. growing or changing into something else). The magic shouldn’t be overly complex, however, such that it becomes confusing to the child as to what is happening in the VE in response to their dragging/clicking/pushing action on the physical device.

• Narrative: constructive and interactive
An ongoing debate in the VR literature is how to allow users in immersive first person virtual worlds to have more control over the ensuing course of events. The term ‘interactive narrative’ has been coined to describe this area. One approach has been to provide plot-branching where the user decides which to select, from a number of pre-stored story segments, as to how to progress the storyline. This method, however, has proved to be disappointing as the child is not asked to construct their own beginning/middle or ending of a story or build their own characters but simply perform a multiple choice exercise. A more promising method has been to provide different viewpoints of the story, allowing the child to see the story unfold through the eyes of different characters (Strommen, 1998). In this way the child is provided with the opportunity to imagine how events appear differently depending on the viewpoint. However, even in this setting the story is still being provided for the child, and is thus not taxing the child to use much of their own imagination or creativity.
Puppet, by contrast, was explicitly geared at providing children with a virtual theatre to support narrative development in a more constructive way. We can see this by revisiting Bruner’s components of narrative understanding in the context of what and how we designed: (1) a sense of agency/purposeful action and (2) of sequential order arise from giving the children a form of scaffolding through a partially constructed narrative and by allowing them to attribute various features (emotions, personality characteristics, sound effects, dialogue). Their understanding of (3) a sense of canonicality, or the progression of a normal or appropriate story is enabled by allowing them, after making changes, to be able to play back the story and observe it in the VE as it unfolds. Finally, (4) a sense of a narrator’s point of view, is facilitated by allowing the child to move back and forth between modes. If children want to change the course of events they can then step back out into one of the editing modules. If they want to enact out different experiences in the VE they can opt for staying in the enactive mode, taking on different avatar roles. Having been scaffolded through all the learning modules they are then given the opportunity to construct their own, complete narrative.

5. Conclusions
We began this paper by suggesting that one profitable approach to designing VEs, is by using what we consider to be a judicious mix of well-known user-centred design methods, theory and previous research. In addition, we noted how important it is to use these in combination with addressing specific design issues to do with the particular properties of virtual environments. We highlighted a number of these in the context of developing VE applications for supporting learning. Our belief is that these do have some wider generalisability than our study not least because of the following. Firstly, we highlight how informed developmental (particularly cognitive) considerations are an important factor in making design decisions. For example, the issues to do with the form of representation (e.g. levels of realism) could not be decided, a priori, without understanding the competences of the children when interacting with both physical and virtual settings. Secondly, we show how it is important to understand the differences between actions (here, play) in the physical and virtual worlds. For example, our set of issues to do with action control and manipulation speak directly to the need to consider whether, in the VE, we wish to emulate or radically differ from the ways that analogous activities are organised in the physical world. While these issues are particularly salient here because children are the end users they do, in principle, apply to any non-expert user group of virtual worlds.

A similar comment applies to our use of what was a quite complex methodology. It has to be said that this is time-consuming and requires considerable effort and expertise. However, we would argue that it is the mix of methods and perspectives that is necessary, however they are implemented, particularly through spending time on informing the early stages of a design project. In particular, many design conflicts and dilemmas can be worked through prior to
any coding taking place, thereby reducing the risk of premature commitment to a technology, interaction style, activity, etc which in the end may prove to be inappropriate, either technologically or developmentally. Of course in commercially-based projects, economic factors such as time and resource limitations may prevent such an extensive methodology from being adopted. However, there is likely to be many benefits, especially in terms of understanding and attaining the goals of the project, even if a 'slimmed-down' version of the approach is adopted.

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