SafeChild: an Intelligent Virtual Reality Environment for Training Pedestrian Safety Skills

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Abstract. Training children safe behavior in traffic situations is both important and challenging. One of the problems is children's limited perceptual-motor abilities and associated difficulties with important cognitive skills required to be safe pedestrians. Existing traffic education programs focus more on theoretical knowledge, while training practical skills in the real world is dangerous, expensive and hard to organize. This paper presents a promising alternative – an intelligent virtual reality training environment that allows children to practice their pedestrian skills. It describes the interface and architecture of the system, as well as the skill model of the pedestrian safety domain. The results of a pilot study showed that children of the target age group rarely had problems with applying (and acquiring) "basic" traffic skills in the developed virtual environment. However, when applying and learning "advanced" pedestrian skills, they required additional support.

1 Introduction

Child pedestrians, especially aged 5 to 9, are endangered traffic participants [1]. According to statistics, just in 2013 in Germany, they were involved in over 3.000 traffic accidents [2]. In USA, more than 11.000 of pedestrian injuries in 2011 happened to children under 14 [3], and the numbers worldwide are also alarming [4]. There are many reasons for children to be especially endangered in traffic. They are hard to see, physically fragile, and their perceptual-motor abilities are still limited [4]. Mentally, children not only lack the knowledge about traffic safety, but also have difficulties with the cognitive skills that are required to be safe pedestrians [1],[5]. On the bright side, several studies indicate that children's behavior on roads can improve significantly through individualized practical street side training [6]. However, a number of requirements must be met for organizing such training. This includes particular weather and traffic conditions as well as sufficient personnel to guide the training and to ensure the safety of children. Yet, even when the requirements can be met, roadside training remains unpredictable and hard to control [5]. Therefore it is very challenging for educational institutions (such as schools and kindergartens) to provide a sufficient amount of practical traffic safety training.

One promising way to tackle these problems is to employ Virtual Reality (VR) and conduct such training in virtual road environments that are not only realistic and immersive, but also safe and controllable. With the increase in computing and graphical power of home PCs and the recent emergence of immersive displays and natural, gesture-based input devices on the consumer market, VR can be even brought into private households, which enables parents and children to train whenever they want.

In this paper, we present the SafeChild platform that combines a rich and open-ended virtual city environment with the functionality of Intelligent Tutoring Systems (ITS) to provide children with guided and assisted training in a wide range of training scenarios. We describe the architecture and the interface of the system, the designed domain model of pedestrian safety skills and the set of exercises training these skills. Further, we present a user study evaluating the feasibility of the system, discuss its results and outline plans for future work.

2 Related Work

A number of previous studies have investigated the use of Virtual Reality (VR) as a tool for practical child pedestrian training. In a study by McComas et al., children from 4th to 6th grade attending urban and suburban schools went through a VR intervention that was intended to teach several pedestrian safety skills [7]. The results showed that children were able to significantly improve within the VR application but only the children from suburban schools were able to transfer the improvement into the real world. Another study by Thomsen et al. focused on the skill of finding appropriate gaps in traffic to cross a road with children aged 7, 9 and 11 [8]. The outcome of the study indicated that, after VR training, children were able to cross faster, determine crossing times better and missed fewer opportunities to cross. Further studies that confirm the potential of VR as a tool for training child pedestrians include those conducted by Congiu et al. [9] and Schwebel et al. [10],[11]. VR was also used specifically as a tool for research toward understanding child-pedestrian's deficits of hazard perception abilities by Oron-Gilad et al. [5]. They showed using VR that children are less sensitive to potential hazards and that the ability to detect such hazards increases with age.

In the above-mentioned studies, VR was used primarily as a tool for human teachers and researchers. As a consequence, the VR applications focused on providing a realistic representations of the real world scenarios but lacked diagnostics and tutoring capabilities that could help analyze and interpret learners' behavior, detect errors and deficiencies in higher-level cognitive skills, and guide or assist children through training. Furthermore, these systems were limited in terms of interaction possibilities and training scenarios.

On the other hand, the advantages of combining VR environments with Intelligent Tutoring Systems (ITS) have been addressed both conceptually [12] and practically in other domains. Successful implementations include STEVE – a system for training Navy personnel to use complex machines [13], HERA – a system for training operations at high-risk sites [14], PEGASE – a system used for training collaborative procedures on aircraft carriers and for firefighters intervening high-risk areas [15], etc.

Based on the success of VR as a tool for training child pedestrians and the promising work in other domains on combining VR and ITSs, we have developed SafeChild. It does not only provide a VR environment for training child pedestrian skills, but also analyzes user behavior during training to recognize problematic skills and carry out adaptive guidance.

3 Child Pedestrian Safety Skills

Any ITS requires a Domain Model that describes the knowledge to be taught. For the domain of child pedestrian safety, there are several behavior rules that children need to know and corresponding skills that they need to master in order to become safe pedestrians. In the reminder of this paper, we concentrate on the skills involved in different variations of the road-crossing scenario, which is at the core of any child pedestrian safety training.

Although described with slight variations and different granularity, there is an agreement on a number of core behavior rules with varying degree of difficulty for young children. Van der Molen et al. have analyzed the task of road crossing and decomposed safe execution of this task into 26 sub-tasks [16]. Further, Thomson et al. [17] defined three high-level skills that are mandatory: (I) making judgments about safety of a crossing place; (II) identifying traffic that could pose a threat and (III) integrating information from different aspects of the traffic situation. These high-level skills require a number of underlying abilities that are especially challenging for young children since their cognitive apparatus is still developing [5]. For instance for (I), it is essential to detect potential threats that might not be physically present at the moment. In experiments described in [18], it has been shown that children aged 5 to 7 exclusively rely on visible presence of cars to determine whether a certain place is dangerous to cross. Factors such as obstacles obscuring the view are not recognized as threat by them. For (II), an important skill is to pay selective attention to those parts of traffic that are relevant for one's safety. Hill et al. showed that children aged 4-9 have difficulty paying attention to relevant information and ignoring irrelevant one [19]. Last but not least, for (III), it is important to be able to observe the road from a global perspective, which is also more difficult for young children [20].

We have conducted a cognitive analysis of this domain informed by the existing literature on pedestrian traffics safety and in consultation with traffics safety experts. As a result, we have identified two groups of skills: the "basic skills", which are less demanding cognitively and should be easier for children to apply and master, and the "advanced skills" that involve meta-cognitive processes, more complex planning and decision making procedures and maintaining the awareness of others. For SafeChild, the hierarchical organization of skills becomes an additional source of information to elaborate student modeling (by propagation) and adaptation strategies (e.g., by task sequencing). The complete hierarchy of skills is shown in Fig. 1.

We plan to subject this model to further investigation and examine its robustness toward experimental data. Open research questions include: at which age a certain skill can be trained, whether particular skills should be further decomposed (or combined) and how well improvements of individual skills in VR translates to improvements in the real world.

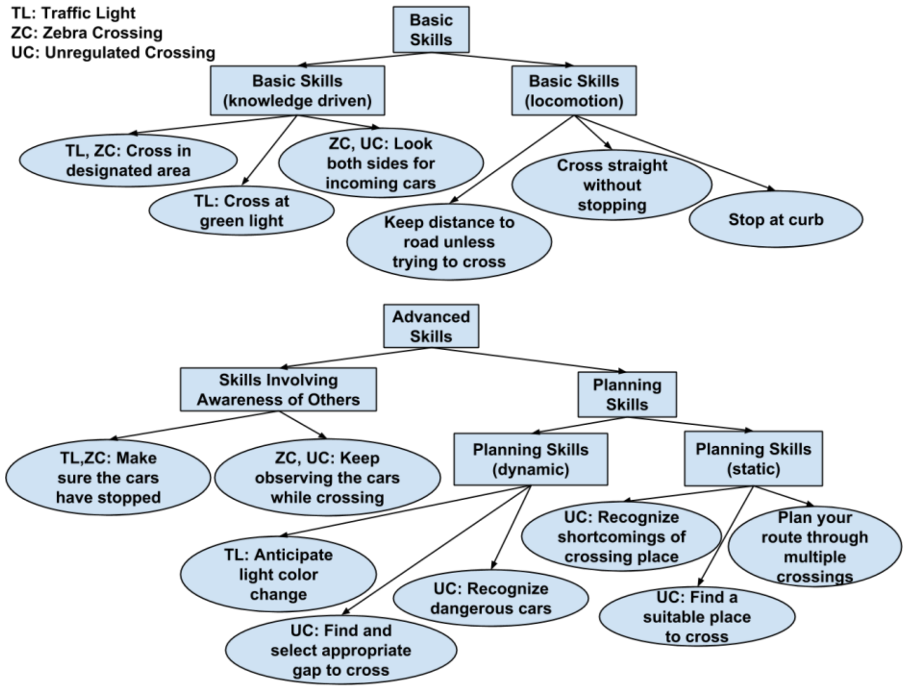


Fig. 1. Skills in SafeChild[1]

4 SafeChild system

The SafeChild system has been designed to support assessment and training of the identified pedestrian safety skills. In general, SafeChild consists of three major components: a VR city environment providing the training area, a flexible interface to interact with this environment and an ITS that monitors learner's behavior, detects correct and incorrect applications of target skills, maintains the detailed representation of learner's pedestrian abilities and supervises the training process.

The VR city environment consists of realistic urban architecture and a traffic simulation developed with the Unity3D game engine. It is freely explorable by the user who can engage in typical pedestrian activities such as crossing the road under different conditions. Several simulation parameters can be adjusted, including car speed, traffic density and walking speed of the user.

The flexible interface supports different display configurations and input devices. The basic setup consists of a standard monitor as the display and a standard keyboard

[1] Zebra crossings are common pedestrian walks consisting of light and dark stripes. Unregulated crossings describes crossings that do not have designated crossing places for pedestrians.

as the input device. This is still the most common setup for home computers nowadays and, since one of the goals for SafeChild is to provide child pedestrian training in private households, the support of this setup is mandatory. However, one can assume that interfaces enabling children to practice in a more natural and immersive way would lead to higher engagement, easier control and better transfer of skills. Therefore, SafeChild has been designed to support a wide range of different input and output devices including multi-monitor setups, Head-Mounted-Displays (HMDs), Gamepads and gesture trackers. Although research on the usability and applicability of such immersive interfaces is still in an early stage, first promising results have been already achieved by combining the Oculus Rift as a display and a combination of Myo armband and Leap Motion hand tracker as input devices [21].

The overall architecture of SafeChild is presented on Fig. 2. It consists of the four typical ITS components [22]: the Domain Model presented in Section 3, the Student Model representing child's current states of learning, the Pedagogical Model that defines how to teach the child and the Interface Model that serves road-crossing exercises (described in Section 4.1). In SafeChild, the Interface Model can be interpreted as the combination of the VR city environment and the flexible interface. The Interface Model is connected to the other ITS components via a designated Instructor Agent described in Section 4.2.

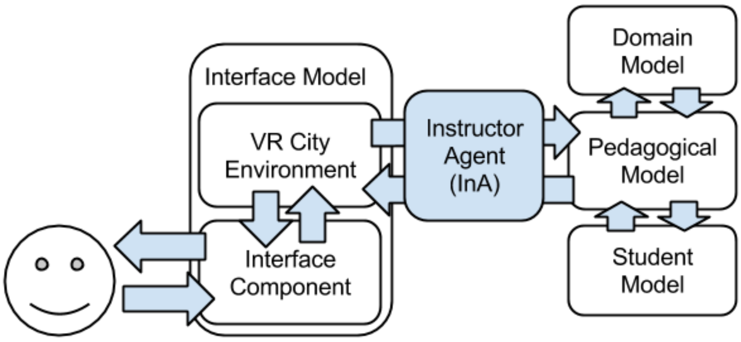
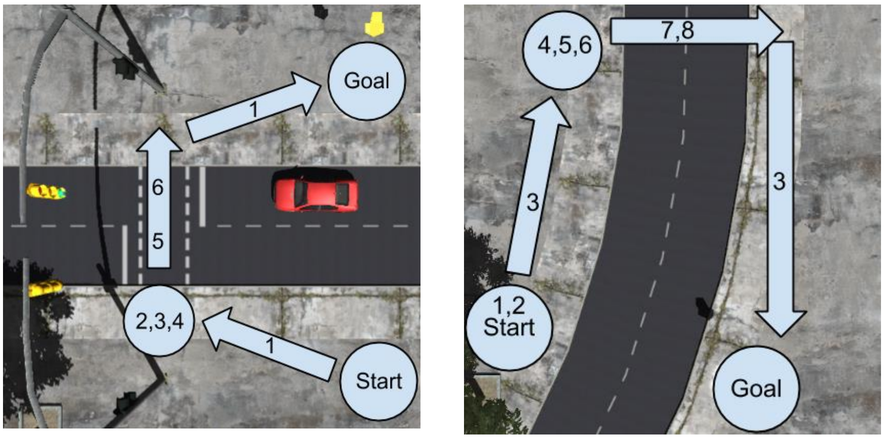


Fig. 2. SafeChild architecture

4.1 Road-Crossing Exercises

In order to help children train skills described in Section 3, SafeChild provides a set of ten road-crossing exercises. Each exercise requires the learner to cross the road under different conditions and, consequently, involves a unique sequence of skills. Fig. 3 shows examples of two exercises with the corresponding skills.



1. Keep distance to road
2. Stop at curb
3. Cross at green light
4. Make sure the cars have stopped
5. Cross in designated area
6. Cross straight without stopping

1. Recognize shortcomings of the crossing place (road curvature)
2. Find a suitable place to cross
3. Keep distance to road
4. Stop at curb
5. Look both sides for incoming cars
6. Recognize dangerous cars
7. Cross straight without stopping
8. Keep observing cars while crossing

Fig. 3. Traffic light and unregulated crossing exercise and corresponding sequences of skills

The complete set of exercises consists of three tasks related to using traffic light; three tasks related to using zebra crossing, three tasks related to unregulated crossings and one combination exercise. For traffic light and zebra crossing, the learner starts once directly in front of the designated crossing area; once, within a small distance, but with the traffic light / zebra crossing still in sight; and once, further away, where a turn in the virtual city environment is required to find the designated place to cross. In all cases, the final goal is directly visible and the learner is supposed to utilize the available regulated crossing to reach it. For the unregulated crossings tasks, the user starts once on a sidewalk next to a straight road without obstacles; once, with a parking truck as an obstacle; and once, close to a road curve obstructing the field of vision. The task is to recognize shortcomings of the crossing place if they are present and cross the road safely. In the final exercise the learner can plan own route to the goal and is given the opportunity to either cross the road once with an unregulated crossing or to cross twice using traffic light and zebra crossing; the expected behavior is to prefer the combination of traffic light and zebra crossings over the unregulated crossing. The left part of Fig. 4 shows a screenshot of an exercise execution process, with the yellow arrow designating the goal. The top-right part of the figure shows the feedback screen generated by SafeChild if the learner fails to achieve the goal (is hit a by a car). The top-bottom part shows the feedback produced after reaching the goal.

Fig. 4. Road Crossing Task from user perspective and GUI overlays for getting hit by a car and reaching the goal.

4.2 Interaction Agent

The Instruction Agent (InA) has two main tasks. First, it observes exercise performance in real-time and determines at any point during training, which skills are required and whether they are being carried out correctly. In the pedestrian safety domain, correct behavior is dependent on dynamic objects such as cars and traffic lights and requires time dependent decision making such as finding the correct time window to cross a road. In order to meet these requirements, a novel method has been developed based on Behavior Trees (BT) [23]. Each exercise is represented by a BT that hierarchically organizes all behaviors required to perform this exercise. One or more skills described in Chapter 3 can be associated to a behavior. During exercise performance, the state of the BT is updated in real-time and indicates for each behavior whether it is currently needed or has already been completed (successfully or not). Depending on the state of the BT, different information about the city environment needs to be enquired in order to carry out the update. However, not all information can be directly retrieved from the raw data of the simulation. For many pedestrian safety skills, it is important that the learner is aware of task-related information within the environment. Therefore, a Short-term Memory Model (SMM) is maintained as well during exercise execution. This model contains information about which objects were visible to the user and at which state the objects had at that time.

The second main task of InA is to carry out in the city environment adaptive instructional interventions produced by the Pedagogical Module. For this purpose, InA includes an Adaptation Controller that is able to change simulation parameters, to manipulate objects in the VR and generate instruction and feedback in the city environment. A complete update cycle that is performed in every frame is shown in Figure 5 and consists of 4 steps. Due to the update mechanisms of a BT, this can be achieved in an efficient manner and is, therefore, suited for real-time environments.

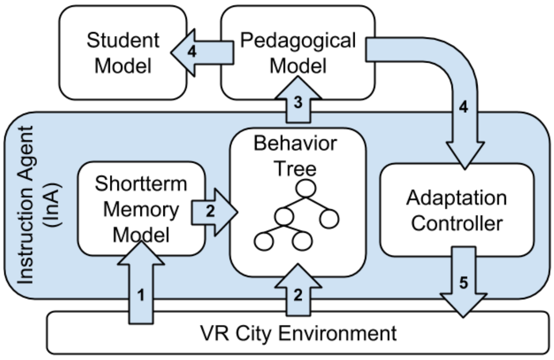


Fig. 5. Instruction Agent (InA) update cycle

1. The current field of view of the learner based on her/his current position and orientation within the simulation is analyzed to update the SMM;
2. Additional information from the simulation is processed together with the Memory Model to update BT;
3. The state of the BT passed to the Pedagogical Model and analyzed to decide whether direct intervention or a student model update is required;
4. Necessary interventions are implemented in the city simulation through the Adaptation Controller and Student Model updates are performed.

Fig. 6. BT state and instructions (1)

In Fig. 6, the behavior tree is shown next to instructions for the following situation. The learner has seen the goal on the other side of the road (which means a crossing is required), but has not yet explored the environment. Thus, a number of nodes within the BT are in the “Running” state, including “Crossing” and “Find a place to cross”. Based on this information, SafeChild can provide the learner with instruction directly adapted to his/her specific situation. Once the learner turns his/her head in the virtual environment and detects the traffic light (Fig. 7), several steps execute. First, the SMM is updated with the information about a safe place to cross the road. Next, the BT is updated and the behavior “Find a place to cross” switches to the “Success” state and causes the behavior “Go to a place to cross” to switch to the “Running” state. As a consequence, the new instructions are presented. Besides generating instructions in the form of direct guidance, a number of additional functionalities can be integrated based on the given information. For instance, the skill “Keep distance from road” is assigned to the behavior “Find a place to cross” and “Go to a place to cross”. Thus the system keeps track of the distance of the learner to the road in this situation and would notice an error and display a warning if it fell below a threshold.

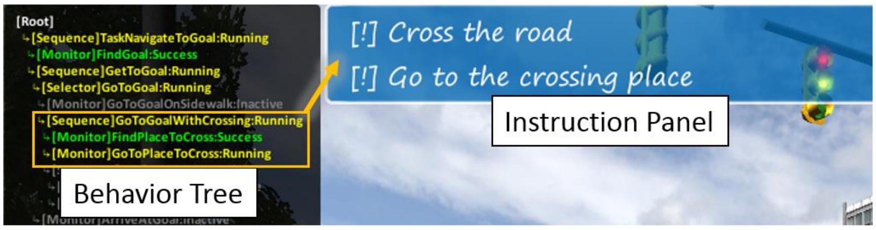


Fig. 7. BT state and instructions (2)

5 Experiment

5.1 Experiment design

The experiment was designed for German-speaking children from 6 to 9 years old to match the critical age group (see Section 1). 5 year olds have been excluded, because (1) we believed that the controls would be too hard for them to use; (2) they are rarely exposed to traffic situations when alone, since they do not go to school yet. The participants were supposed to conduct the experiment at home, under the supervision of their parents. The required application was provided to the volunteers as a Web-application and also as a download. The application itself contained detailed information and instructions for parents and children. Parents were involved for several reasons. As they hold the main responsibility for traffic safety education of their child, by supervising the study, they could detect her or his individual weaknesses and misconceptions and work on them after the study. Parents could help children with the controls and completing the questionnaires (but were asked to avoid helping with completion of the exercises), and provide us with valuable feedback on the SafeChild approach and implementation. Last but not least, they could choose the most convenient time and place to conduct the study.

The application for the pilot study was a customized version of the SafeChild platform. Once started, it guides the participant through the three steps of the experiment: (1) A pre-questionnaire, (2) a set of road crossing tasks within the SafeChild city environment and (3) a post-questionnaire. The application does automatically log experiment data to a webserver. This data includes questionnaire answers as well as replayable log files for each road-crossing task.

5.2 Pre- and post-questionnaires

The pre-questionnaire consisted of seven questions; it focuses on children's demographic data (age, gender) and prior experience with traffic safety education and digital gaming. The post-questionnaire also continued seven questions asking about the just completed road-crossing tasks and the overall SafeChild experience. This included children's general attitude toward the approach, their opinions on whether they could learn something in such an environment, and whether the environment was realistic. Further children were asked if they got tired during the experiment, and whether or not the controls and the tasks were too hard or too easy. The last two questions asked the parents whether they helped their child and if so, to provide comments on how they helped (in the beginning of the experiment parents were instructed to avoid helping with the tasks themselves). They were also given the opportunity to provide comments on the general approach.

5.3 Road crossing tasks

All ten exercises describe in Section 3.1 and a familiarization task at the beginning had to be completed in the experiment. The simulation parameters used for the road-crossing task were chosen to match the real-world conditions: car speed was around 50 km/h (the upper speed limit in German cities) and the walking speed of the child was set to 1.2 m/s (a common speed for 6 year olds [24]). For the "unregulated crossing" tasks, the frequency of incoming cars was high in the beginning and decreased over time to create larger gaps. Since the study was designed to be conducted by parents with their children in their own home, the standard interface configuration consisting of one monitor and keyboard was used. The controls were based on 6 keys for forward and backward movement, turning left or right and turning the head left or right. Head turning were included as separate action to allow the participant to look to both sides while crossing the road. The preliminary ITS functionalities were not activated for the study due to the immature state and because the goal was to obtain baseline performance data.

6 Discussion of the results

6.1 Questionnaire analysis

The general feedback about the current version of the SafeChild platform was positive. Most children (8 out of 10) liked the overall experience, and, even more important, most of them believed that they could improve their pedestrian skills through such training (9 out of 10). Children also considered the traffic simulation realistic (9 out of 10). However, when it comes to navigating in this simulation, only 4 out of 10 thought the controls were easy to use – all of them were the older children. This indicates that the current keyboard control method could be too demanding, and/or requires additional training, especially for 6-year-olds. Half of the children considered the exercises to be too easy, although none of them was able to demonstrate all required skills and three of them failed on more than a half of the advanced skills. An explanation could be that when these children were able to complete most of the tasks, they assumed that they performed correctly even when exhibiting unsafe pedestrian behavior. Regarding the level of fatigue caused by the tasks during the experiment, most of the children said that they did tire while participating. This result matches with the observation of the tasks performances where children sometimes needed more than six minutes to finish an exercise. As a comparison, adults are able to finish the entire sequence of exercises within the same time. The problems with the controls also may be a factor here. Finally, seven parents reported that they helped their child a little, but limited the help to the controls and not completing the tasks.

To summarize these results, the SafeChild approach appears to be on the right track, when it comes to delivering appealing, realistic, and potentially useful pedestrian safety training, but we need to solve the problems with controls. It also indicates that children do need additional support and guidance during such training. Therefore, we believe that implementing intelligent tutoring functionality can be an effective solution here.

6.2 Performance on traffic task

Any traffic task implemented in SafeChild can have only two outcomes: if a child crosses the street and reaches the goal, it is a success; if a child is hit by a virtual car, it is a failure. Out of 96 completed tasks, 82 constituted successful attempts and 14 – car hits. However, even when the goal is reached, it does not mean that the child has exhibited correct (safe) behavior and successfully demonstrated all the pedestrian skills involved in the task. In fact only 15 times were tasks solved without a single failed skill. It is important to understand, that due to the fact the SafeChild problem-solving environment is highly dynamic with random-generated elements, children can get lucky and complete a task without applying some necessary skills. However failing skills on a regular basis will eventually result in a car hit, which is rather similar to real-life traffic situations. We formulated the following hypotheses to analyze how successfully children apply and improve different skills in SafeChild:

- learners perform significantly better on basic skills than on advanced skills.
- learners learn basic skills significantly more easily that advanced skills.

In order to test our first hypothesis, for each learner, we have computed his/her average basic skill performance and average advanced skill performance. Then we could compare their means using the paired t-test. The test shows that on average a learner performs significantly better on basic skills (M = .93; SD = .04) than on advanced skills (M = .53; SD = .17), $t(9) = 8.11$, $p << .001$, $d = 2.56$. Both the p-value and the Cohen's *d* indicate a very strong difference between the two variables.

The version of the SafeChild environment used in the study did not provide children with many opportunities to learn new skills. Basically, the only instructional support that the system gave was the immediate knowledge-of-result feedback at the end of a task completion. A failure to apply a particular skill, which leads to a car hit, triggered an error message. This allowed a child to self-reflect on what s/he had done wrong and, next time, exhibit a safer behavior. Having this in mind, we analyzed the logs of 14 incorrect task attempts and identified the skills responsible for each failure. In some cases a combination of skills was causing an incorrect attempt (e.g. “find an appropriate gap to cross” and “keep observing traffic while crossing”); and in some cases, it was hard to decide, which of the two skills is responsible (e.g. “recognize shortcomings of crossing place” and “find a suitable place to cross”). In such situations, both skills were treated as the cause. After each such case, we looked if there was another opportunity for a child to reflect on her/his error and apply the skill correctly. We found seven such occurrences: three, when the causing skills were basic and four, when they were advanced. Remarkably, in all three “basic” cases, children have been able to correctly apply the failure-causing skills on the next iteration and never failed it again, including the new context of the combined traffic tasks. On the other side, all four cases of failed advanced skills were followed by more occurrences of the same behavior. This means, even with minimum instructional support children could improve their incorrect traffic behavior, when they need to acquire a basic skill and even transfer it to a novel context, but, without additional support, they cannot master the advanced skills and keep exhibiting the same dangerous behavior even after failing several traffic tasks.

This, essentially, confirms the results previously reported in the traffic education literature [5] that children have far more problems with the advanced pedestrian skills and additionally indicates that any tutoring software built for child pedestrian safety, should focus on these skills.

6.3 Limitations of the study

Despite the interesting results obtained during the study, there are a number of limitations that need to be considered when analyzing the results. First, the experiments were conducted in a home environment and the level of support provided by parents was not observable. Second, there was no sound in the simulation that could have warned children of incoming cars and third the interface and especially the keyboard based controls were difficult for many participants. The results of the study are nonetheless valuable to pilot the approach, elicit the general attitude of the target population towards the system and validate important hypotheses that will influence the future design and to define the next steps for the SafeChild platform. We have been able to achieve all these goals with the conducted study.

Another important drawback of the experiment is the small number and high variability of subjects. It is important to underline, that 6-years-olds and 9-years-olds are very different categories of traffic safety learners. Not only do they possess very unequal amounts of real worlds traffic experience, but also they significantly differ in terms of development of cognitive and perceptual-motor abilities important for mastering pedestrian safety skills, controlling themselves in a VR and cognitive transfer. We have been able to observe it firsthand, as the data generated by 9-years old children and 6-years-old children vary substantially. For examples, according to Piaget, before the age of 7, children remain egocentric in their thinking, having problems perceiving the world from the viewpoint of others. In the future, SafeChild will explicitly account for age as one of core learner parameters.

7 Conclusion and future work

In this paper an analysis of the child pedestrian safety education domain was presented with regard to its requirement toward an intelligent VR training application. The main focus of this work was on the extraction of skills that such a system should target and support and forming a foundation for a structural representation and a method for determining these skills for an individual learner. For this purpose, a user study was conducted with 6-9 years old children using the SafeChild platform. The results of the study indicate that while having almost no problems with applying and acquiring basic traffic skills in SafeChild, children require additional tutoring support on applying and learning advanced pedestrian skills.

Our future work will continue along the two main directions. We will use the results of the described study to develop (in consultation with pedestrian safety experts) the pedagogical model of the SafeChild ITS that will especially target the advanced skills and support children in mastering them. We will continue our analysis of the pedestrian safety domain to refine a more structured representation taking into account types of relations between the skills and adding important conceptual knowledge elements. We also plan to conduct another user study of SafeChild using a more immersive VR setup and more convenient set of controls. This last goal might require development of a more elaborate mechanism for modeling learner perception and intention, as the flexibility of the interface would inescapably cause the input channel to become more noisy and low-level [26].

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