An Immersive Virtual Peer for Studying Social Influences on Child Cyclists' Road-Crossing Behavior

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Abstract—The goal of our work is to develop a programmatically controlled peer to bicycle with a human subject for the purpose of studying how social interactions influence road-crossing behavior. The peer is controlled through a combination of reactive controllers that determine the gross motion of the virtual bicycle, action-based controllers that animate the virtual bicyclist and generate verbal behaviors, and a keyboard interface that allows an experimenter to initiate the virtual bicyclist's actions during the course of an experiment. The virtual bicyclist's repertoire of behaviors includes road following, riding alongside the human rider, stopping at intersections, and crossing intersections through specified gaps in traffic. The virtual cyclist engages the human subject through gaze, gesture, and verbal interactions. We describe the structure of the behavior code and report the results of a study examining how 10- and 12-year-old children interact with a peer cyclist that makes either risky or safe choices in selecting gaps in traffic. Results of our study revealed that children who rode with a risky peer were more likely to cross intermediate-sized gaps than children who rode with a safe peer. In addition, children were significantly less likely to stop at the last six intersections after the experience of riding with the risky than the safe peer during the first six intersections. The results of the study and children's reactions to the virtual peer indicate that our virtual peer framework is a promising platform for future behavioral studies of peer influences on children's bicycle riding behavior.

Index Terms—Virtual humans, virtual reality, applied perception, 3D human-computer interaction.

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1 INTRODUCTION

Peers exert a strong influence on the actions and attitudes of school-aged children. Friends and siblings provide role models that affect how children see themselves. This influence extends to judgments of physical ability and decision-making in performing physical tasks [1]. The confidence gained by watching a peer succeed in performing a risky task can cause children to overestimate their own capabilities and lead to dangerous behaviors that put them at risk of injury or death. One of the most dangerous activities that children perform without adult supervision is crossing traffic-filled roadways on a bicycle [2]. Bicycle crashes are among the most common causes of severe injuries in childhood [3]. Children between the ages of 5 and 15 are particularly vulnerable, with the highest rate of injury per million cycling trips. One third of the accidents are the result of motor vehicle-bicycle collisions, resulting in fatalities in 90 percent of those cases [4].

The goal of this research is to develop a programmatically controlled peer in an immersive, interactive bicycling simulator to ride with a human subject for the purpose of studying how social interaction with a peer influences children's riding behavior. Controlled experiments of children's bicycling in traffic cannot be conducted on real roads because of the risk of serious injury to participants. Virtual environments offer the potential to study bicycling behavior in a realistic, but safe setting.

In our previous work, the Hank bicycling simulator (Fig. 1) was used to study perceptual-motor factors [5] that put children at risk for car-bicycle collisions. This research revealed key differences in how children and adults cross traffic-filled roads. When crossing a stream of traffic, children and adults choose the same size gaps to cross, but children end up with less time-to-spare between themselves and the approaching car when they clear the path of the approaching car. Analysis of the crossing behavior revealed that there are two reasons why children have less time-to-spare than adults: 1) children delay initiation of crossing, and 2) children take longer to reach the roadway [5]. This puts children at greater risk of injury than adults.

Our previous studies involved solo riding by the participants. The influence of peers such as friends or siblings on rider attention, decision-making, and performance is unknown. The addition of an interactive virtual peer in our immersive bicycling simulator enables us to examine the difficult-to-study problem of how peers influence children's road-crossing behavior in the context of natural multimodal interaction (Fig. 2).

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Fig. 1. Immersive bicycling simulator.

In prior research, interactive virtual humans have been used to train verbal and nonverbal social behaviors in face-to-face conversation [6], [7], [8], [9], [10]. To our knowledge, no studies have used virtual human agents to study the social influence of peers on skilled perceptual-motor behaviors in everyday activities that involve physical risk taking, such as bicycle riding through traffic-filled intersections.

1.1 Contributions

The addition of a virtual bicyclist in an immersive virtual reality simulation presents significant technical challenges that are distinct from those usually encountered when developing virtual humans in interpersonal face-to-face scenarios. The main contributions of this work are:

- A reactive component that controls the gross motion of the virtual bicyclist by adjusting the acceleration and speed to produce a range of natural riding motions including riding abreast of the human rider, stopping at intersections, and crossing traffic.
- An action-oriented animation behavior component that controls the fine animation actions of the rider, producing natural behavioral actions, such as pedaling, adaptive gaze, and stopping and starting motions with smooth transitions between actions.
- A model for synchronizing the gross motion and fine animation actions of the virtual rider. For example, the rider adaptively switches from coasting to pedaling based on the rate of acceleration.
- Socially interactive verbal and nonverbal behaviors for initiation, interaction, and disengagement with fellow riders.
- Coordination of traffic generation and peer riding behavior to precisely control the selection and timing of gap crossing to simulate safe and risky riding behavior for human riders.
- Evaluation of our virtual peer framework in a study in the Hank bicycling simulator. The results of our study revealed a significant social effect of risky versus safe behaviors of the peer on children's tendency to stop at intersections and on the frequency with which intermediate-sized gaps are crossed. Qualitative evaluations revealed that children paid attention to the virtual peer, perceived the peer as a social riding partner, and thought that the peer provided a good example of bicycle riding behavior. This work demonstrated that immersive virtual humans can be successfully used to study peer influences on children's bicycling.

Fig. 2. Female rider standing alongside a female peer (Erin) in the bicycling simulator.

2 RELATED WORK

2.1 Virtual Humans in Training and Pedagogy

Many virtual human interfaces have been developed for training, pedagogy, and education. These interfaces provide feedback to human users through multiple verbal and nonverbal channels such as speech, gestures, and facial expressions. Rea, built by Thorisson and Cassell, is a virtual real estate agent capable of understanding speech and gaze [11]. Rea keeps a model of interpersonal distance with the user, and employs small talk to reduce interpersonal distance if she notices a lack of closeness with the user. Research with Rea demonstrates that using both speech and gesture contribute to virtual humans being perceived as life-like and believable. Slater and coworkers found that theatrical actors and directors could effectively use virtual humans for rehearsals before a live performance [12]. The Mission Rehearsal Exercise (MRE) system is an immersive virtual reality system with life-size virtual humans that was created to teach users leadership skills in task-oriented social situations [9]. The MRE uses fictional scenarios based on the real world to give communicative training. ELECT BiLAT, developed at the ICT at USC, is a game environment with virtual humans that teaches army officers culture-specific verbal and nonverbal behaviors in Middle Eastern culture [13]. Babu et al. showed that immersive virtual humans in natural multimodal interaction can teach and train users social conversational nonverbal behaviors associated with south Indian culture [14].

2.2 Responses to Virtual Humans

A number of researchers have investigated how people respond to computers and virtual humans. Nass and Moon have shown that people readily attribute human characteristics to computers, and react to the computer's "helpfulness," "expertise," and "friendliness" [15]. Zanbaka et al. found that people respond to virtual humans similarly to the way they respond to real humans [16]. They were able to elicit social inhibition from female participants in response to a virtual human observer. Slater et al. at UCL have conducted studies on the social ramifications of having avatars in virtual environments. They were able to elicit emotions such as embarrassment, irritation, and self-awareness in virtual meetings. They also found that the presence of avatars was important for social interaction and task performance [17]. Raij et al. examined perceived similarities and differences in experiencing an interpersonal scenario with a real and virtual patient [18]. They found that both level of immersion and natural interaction were important in facilitating the participants' ability to perform a training task with a virtual patient as effectively as with a real patient. Babu et al. showed that a virtual human receptionist can engage users in both social and task-oriented conversations [19].

We have found no work that directly focuses on using interactive virtual humans in an immersive virtual environment to study human perceptual-motor behaviors such as road crossing. We propose a framework for the design and implementation of a virtual peer to ride alongside real riders in an immersive bicycling simulator.

In the following section, we discuss the components of the virtual peer framework as part of the Hank bicycling simulator.

3 COMPONENTS OF THE VIRTUAL PEER SYSTEM

3.1 Overview of the System

Our high-fidelity real-time bicycling simulator is pictured in Fig. 1. A stationary bicycle is mounted in the middle of three 8 ft high by 10 ft wide screens placed at the right angles relative to one another forming a 10 ft × 10 ft area. Three Projection Design F1+ projectors are used to rear-project an image of size 1,280 × 1,024 pixels onto each of the screens, providing participants with 270 degrees of non-stereoscopic immersive visual imagery. The viewpoint of the scene is adjusted for each rider's eye height.

The bicycle is instrumented to sense steering angle and pedaling torque applied by the rider. These sensed values are combined with virtual terrain information and a bicycling dynamics model to compute bicycle speed and direction. The bicycling dynamics model accounts for rider and bicycle mass and inertia, virtual terrain slope, ground friction, wind resistance, etc.

Computationally, the system is a distributed environment hosted on seven PCs connected via a network. The simulation engine is hosted on a single PC; a second machine is dedicated to dynamics for the instrumented bicycle; each of the three screens has its own PC for rendering graphics; one PC provides sound processing; and one performs video recording.

The simulation software is divided into motion control for dynamic objects and animation/graphics rendering. The simulation engine (*Hank*) computes position and orientation for each dynamic object (vehicle, virtual or human rider) on each step of the simulation. This information is then transmitted to graphics PCs, where it is processed by the *Visualizer* application to update the scene graphs and render a corresponding image for each of the screens. The graphical and animation behavior components of the virtual peer are all integrated into the *Visualizer* application.

3.2 The Rider's Experience

What is it like to ride with the virtual peer? Here is a sample interaction scenario between a child *rider* and the virtual bicyclist *peer, Alex*.

The simulation starts with Alex greeting the rider (Fig. 3a). He looks at the rider, smiles, gestures a greeting and says: "Hi, my name is Alex! We are going to ride together for the next six blocks. When we get to each intersection, I'm going to show you how to cross the traffic. After I cross, then it will be your turn to cross. I will wait for you on the other side of the intersection, and then we will go to the next one. Are you ready?" The child responds: "Yes!" As the rider starts bicycling, Alex, who was waiting patiently, rides alongside the child. Alex keeps pace with the rider, trying to stay alongside and watching the rider from time to time to make sure the rider is keeping up with him (Fig. 3b). If the rider speeds up or slows down, then Alex also gradually speeds up or slows down to stay abreast of the rider. As Alex approaches the intersection, Alex slows down, stops at an appropriate distance from the edge of the intersection (independent of what the rider does), and puts his foot on the ground (Fig. 3c).

Alex looks at the rider to make sure that the child has reached the intersection. Then, Alex gazes at the stream of vehicles approaching the intersection. Alex waits for a suitable gap in traffic to appear, and then crosses the intersection timing his motion carefully to safely pass between two vehicles (Fig. 3d). When Alex gets to the other side of the intersection, he stops and waits for the rider to cross. As the rider approaches Alex on the other side of the intersection, the peer mounts the bike and gradually increases speed to match the speed of the rider and continues to ride alongside the child to the next intersection.

After crossing six traffic-filled intersections, Alex stops at an empty intersection. Alex glances at the rider and says, as he waves his hand, *"I've got to go now, so you will be crossing the last six intersections by yourself. Thanks for riding with me!"* (Fig. 3e, left). Alex turns left and rides away along the side road (Fig. 3e, right). The rider continues to ride ahead alone, crossing another six intersections with traffic.

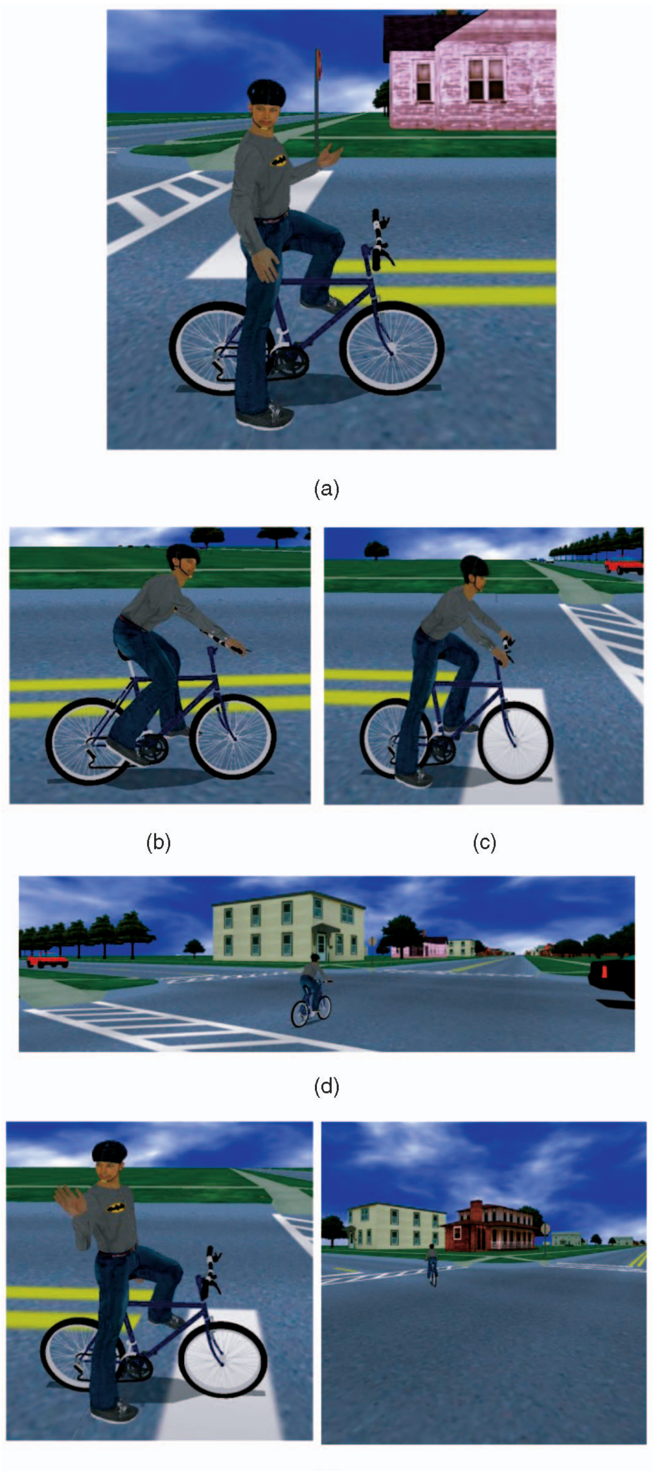
3.3 Peer Requirements: What Makes This Hard and Interesting

The primary goal of the virtual peer is to serve as a flexible, yet precise tool for conducting experiments. At the same time, it should provide a compelling interactive experience for the child participant similar to the scenario described above.

A key technological challenge in our virtual peer simulation is the need for the peer's cycling behavior to dynamically respond to the subject's riding behavior. For example, the peer should continuously adjust its speed so that it remains abreast of the rider as they jointly ride from intersection to intersection.

If the human rider slows down to a stop between intersections, then the peer should also slow and stop next to the rider with an appropriate change in stance to give the appearance of stable support. This requires tight coordination between the code that controls the dynamic motion of the peer through the environment and the code that controls the animation of the peer model.

As an experimental tool, the peer should offer the researcher fine-grained control over his or her intersection-crossing behavior. The researcher should be able to specify where the peer is positioned as he or she waits for the gap, which gap the peer will choose, when the peer will start to cross (relative to the lead vehicle of the gap) and at what acceleration rate the peer will move into the chosen gap. It is also important to control the stream of traffic to specify which gaps are available for the peer and the child rider to cross and which exact gap in the stream the peer will cross.



(a)

(b)

(c)

(d)

(e)

Fig 3. Interaction scenario between the rider and Alex. (a) Initiation: Alex greeting the rider and asking the rider to ride alongside him for the next six blocks. (b) Alex riding alongside the rider. Since Alex is to the left of the rider, he is rendered on the left screen. (c) Alex waiting at the intersection gazing at approaching vehicles, looking for an appropriate gap in traffic to cross. (d) Alex passing between two vehicles in traffic. (e) On the left, Alex waving goodbye, and disengaging with the rider. On the right, Alex riding away onto side road at the intersection.

At the same time, the experiment should not appear scripted or predictable for a child rider. The virtual peer should provide a plausible representation of a child bicyclist with respect to visual appearance and behavior such as natural pedaling motions as well as interaction with the participant. It is also important for the peer to demonstrate attention to the task at hand, e.g., his or her gaze should be drawn to the approaching vehicles to give the impression that the peer is assessing the gaps for crossing.

In the following sections, we describe the components of the virtual peer system designed to meet the challenges described above. First, we focus on the behaviors that control the gross motion of the peer's bicycle. Second, we describe the animation system that produces gestures, utterances, and fine motions of the bicycle and peer. Lastly, we focus on the integration of motion control behaviors with the animation of the peer.

3.4 Motion Control Behaviors for Virtual Bicyclist

The motion control subsystem builds on our earlier work developing autonomous behaviors for virtual cars [20]. Peer behaviors are tied to a sophisticated representation of the road network that supplies information about the structure and geometry of roads and intersections, traffic signs and lights, and the locations of all objects on the roadway [21].

The gross movement of the peer is controlled by a set of motion controllers that determine the steering direction and forward acceleration of the bicycle. The bicycle is modeled as a two-wheeled vehicle that is articulated at the front fork. The speed of the peer's bicycle is constrained to be positive so the bicycle can only move forward. The steering direction is controlled by a pursuit point tracking algorithm. At each time step of the simulation, a point on the road ahead of the peer's bicycle is selected. The circular trajectory that intersects this point and is tangent to the rear wheel is computed. The front fork is then adjusted to be tangent to this circle. An integration procedure updates the speed and position of the peer's bicycle based on the output of the active acceleration controller and moves the bicycle along the circular trajectory that is tangent to both the front and back wheels of the bicycle.

The acceleration of the peer is determined by three independent acceleration controllers, each responsible for some aspect of riding: The ***cruising*** controller initiates the motion of the peer to cross intersections; the ***tandem*** controller sets acceleration so that the peer rides alongside the human rider; and the ***stopping*** controller sets acceleration to bring the peer to a halt at a specified place on the road. The controllers are conditionally activated based on the location and speed of the virtual rider as pictured in Fig. 4.

The peer is initially placed at a stationary position on the road with the stopping controller activated. The peer will remain at this location until the experimenter presses a key to deactivate the stopping controller and activate the tandem controller.

The tandem controller enables the bicyclist to ride alongside the child rider matching the child's speed. Over time, this controller will produce accelerations such that the virtual bicyclist rides abreast the human rider with the desired offset and matched speed. One can think of this controller as a virtual spring attached to the peer to keep him or her adjacent to the child rider. The tandem controller is implemented as a proportional-derivative (PD) controller [22] that computes acceleration for the peer, a_s as follows:

$$a_s = k_p \times (O_l - \Delta x) - k_v \times \Delta v, \tag{1}$$

where Δx is the difference between the position of the peer (in the local coordinate system defined by the road axis) and

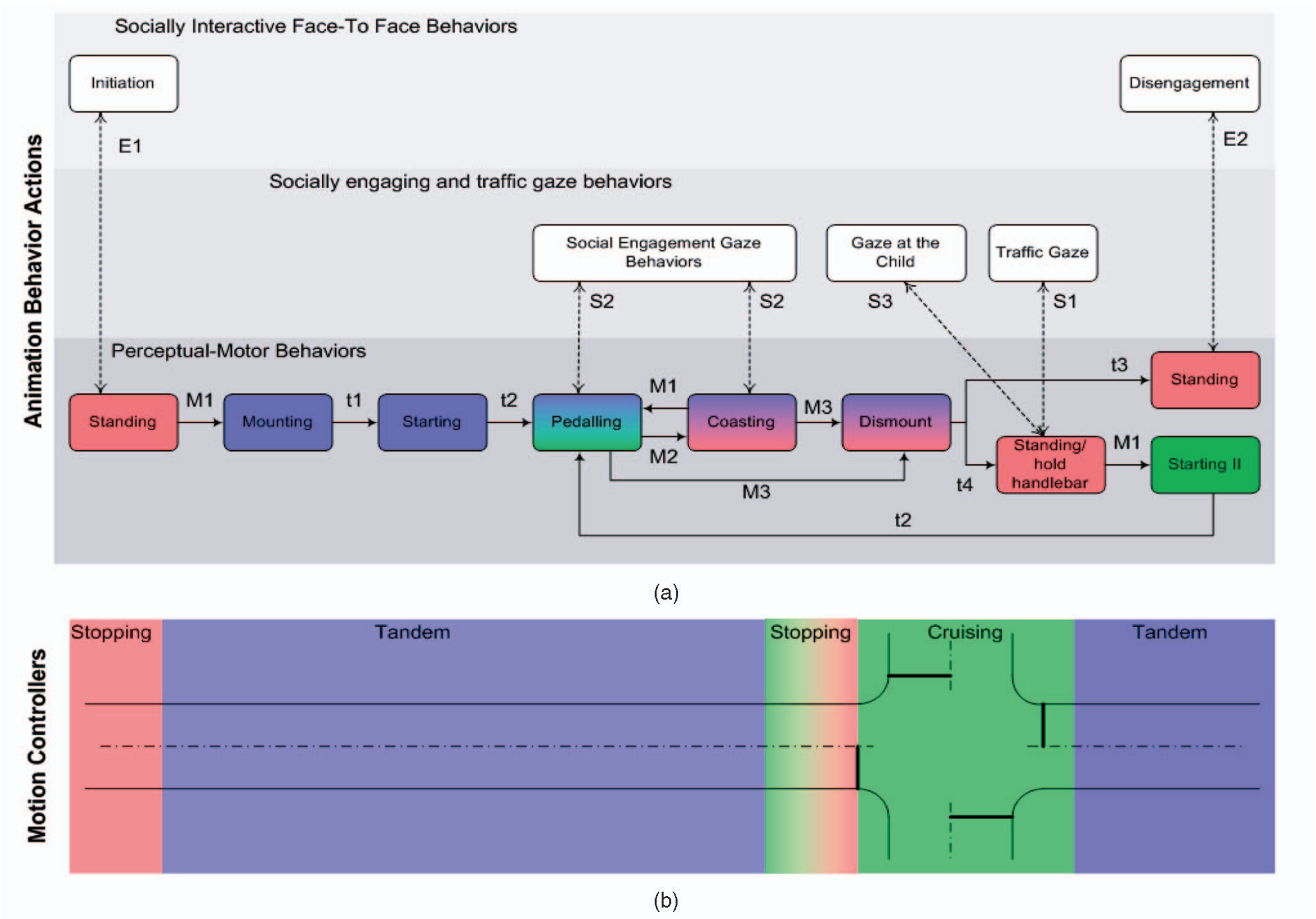


Fig. 4. (a) The state machine that controls the activation of animation behaviors. Solid lines represent transitions between behaviors; dashed lines indicate that behaviors are simultaneously active. The labels on transitions represent the triggers that cause the transition to fire based on time since activation (t1, t2, t3, and t4), social engagement and traffic gaze following criteria (S1, S2, and S3), motion state (M1, M2, and M3), or activation by the experimenter (E1 and E2). (b) The sequence of activations of motion controllers as the peer travels from left to right on the road. The colors indicate which controller is active when the peer is on each section of the road. The coloring of the perceptual-motor animation behaviors in the top panel shows what motion controllers may be active at the same time the perceptual-motor behavior is active. For example, when the peer is pedaling, either the cruising or tandem motion controllers is active.

the position of the child, O_l is the desired offset of the peer relative to the child (positive offset corresponds to the peer being ahead of the child), $\Delta\nu$ is the difference in speed between the peer and the child, k_p is a proportional gain parameter, and k_v is a damping parameter equal to $2.0^* \sqrt{k_p}$ for critical damping.

To keep the peer in view of the human rider on the side screen, we set the desired offset to be slightly positive ($O_l = 0.5$ m). This causes the peer's bicycle to be approximately centered on the front wheel of the human rider's bicycle. The gain parameter determines how quickly the peer responds to accelerations and decelerations of the human rider. Based on preliminary tests, we found that a value of $k_p = 1.5\ \mathrm{s}^{-2}$ allowed the peer to adjust to normal starts and stops without appearing to be abrupt.

At intersections, the virtual peer's motion must be decoupled from the human rider to ensure that virtual peer stops at an appropriate location, waits for a specially designated *target gap* in the stream of vehicles on the crossing roadway, and then safely crosses the intersection. As the peer approaches the intersection, the tandem controller is deactivated and the cruising controller takes over to ensure that the peer will reach the designated stop line position independent of the actions of the child. To maintain continuity of the peer's motion, the speed of the peer is kept constant as it switches from tandem behavior to cruising. When the peer's expected time of arrival at the desired stopping point (based on current speed) is 10 seconds, the stopping controller becomes active and gradually brings the peer to a stop at a specified distance from the crossroad. Based on the peer's current position and speed, the stopping controller computes the constant acceleration rate that will bring the peer to a stop over a specified distance.

After coming to a stop, the peer waits for the target gap. When the target gap reaches the intersection, the stopping controller is deactivated and the cruising controller accelerates the peer at a constant rate until a desired speed is reached. The acceleration rate and desired speed were set to produce a trajectory that approximately matched the performance of human riders in the simulator. Based on the analysis of intersection crossing by children in previous experiments, we set the acceleration rate to $4\ \mathrm{m/s}^2$ and the desired speed to be $6\ \mathrm{m/s}$. The controller maintains this desired speed until the peer crosses the intersection. The timing of the initiation of movement is precisely linked to the motion of the target gap. We discuss the mechanism for coordinating bicyclist motion to the arrival of the gap in Section 3.7.

Once the virtual bicyclist enters the next block of the roadway, the cruising controller is deactivated and the tandem controller is activated. Because the human rider is far behind, the tandem controller will produce negative acceleration and bring the peer to a stop to wait for the human rider to cross the intersection (the acceleration produced by the tandem controller will be negative, but the virtual peer cannot move backwards). When the human rider crosses the intersection and approaches the peer, the tandem controller will switch to positive acceleration, allowing the peer to continue to the next intersection.

3.5 Virtual Peer Rendering and Animation

3.5.1 Visual Components of the Virtual Peer

The fine motions, gestures, and speech of the virtual peer were built using Virtual Human Interface Framework (VHIF) [10]. VHIF integrates components for rendering, behavior modeling, and support for multimodal interaction. Virtual humans were created and animated using interactive 3D characters from Haptek Corp. and then integrated into the Open Scene Graph framework (OSG) to render the graphics in the Visualizer. Haptek provides tools for predefining animation actions, runtime motion generation and blending of verbal and nonverbal output, and 3D character modeling. To ensure high visual fidelity, a boy (Alex) and a girl (Erin) virtual peer were modeled using pictures of a real 10-year-old boy and girl with tools provided by Haptek Corp. for virtual human authoring. Accessories for the virtual peers such as the helmets and the bicycle components, were modeled using 3DS Max. The virtual bicycle wheel rotations were rendered based on the distance traveled by the peer between the previous and the current simulation frames. Bicycle crank rotations were matched to the pedaling rate of the virtual peer.

Speech utterances of the virtual peers for initiation and disengagement were implemented using prerecorded voices of a 10-year-old boy and girl, and runtime lip synchronization was predefined using the Haptek animation framework. The virtual peer's verbal behaviors were tailored to reflect appropriate intonation and pitch. Verbal and nonverbal behaviors of the virtual humans including timing and synchronization of gestures, body movements, postures, facial expressions based on emotion, and speech utterances were implemented as a finite state machine of behavior animations in VHIF [10].

3.5.2 Animation and Discourse Behaviors

Using VHIF, an animation and discourse model was built for the peer. This model consisted of a prescripted tree of behavioral actions producing social face-to-face interaction behaviors and fine motor behaviors. Using the scripting tool, the state machine of animation behaviors can be predefined to stay in a loop, or execute once and then proceed to the next behavior. A runtime motion generation engine blends between animations to produce smooth transitions between behaviors. Fig. 4 shows all possible behavior actions and their triggers. Behavior actions were categorized into socially interactive face-to-face behaviors, socially engaging and traffic gaze behaviors, and perceptual-motor behaviors.

Socially interactive face-to-face behaviors were defined as a combination of verbal and nonverbal behaviors for Initiation (greeting the rider) and Disengagement (saying goodbye). These behaviors were triggered via a keystroke by the experimenter (labeled as E1 and E2) and, once completed, automatically transitioned back to the initial Standing behavior.

Perceptual-motor animation behaviors for bicycle riding such as Starting, Stopping, Pedaling, and Coasting were triggered by a combination of automatic transitions by time-out (labeled t1, t2, t3, and t4) and messages from reactive motion controllers (labeled M1, M2, and M3). The coordination of perceptual-motor behaviors and motion control is discussed in Section 3.6.

A bicycle tilt animation was implemented and was evoked by the system during standing to show a partial dismount of the peer. The peer leans the bicycle and places one foot on the ground for support. This behavior is called Dismount. When standing at intersections, the peer keeps his hands on the bicycle handlebar. When standing to initiate or disengage with the rider, the peer stands with his hands free from the bicycle handlebars. This allows the peer to communicate with the human rider using a combination of verbal interactions and nonverbal gestures during Initiation and Disengagement behaviors. These specialized dismount behaviors were activated by the system based on context of the interaction, i.e., in preparation for social interaction or for traffic crossing. A complementary animation to bring the bicycle to an upright position is evoked by the Mounting behavior. The Mounting behavior then leads to the Starting behavior, followed by the Pedaling behavior, via automatic transitions (Fig. 4).

Socially engaging gaze and traffic gaze behaviors ran synchronously on top of the behaviors defined above. The algorithms for gaze behaviors were implemented in the Visualizer, and were executed by the system based on the location of the peer or the type of task performed by the peer. These algorithms will be discussed in detail in the following section.

3.5.3 Socially Engaging and Traffic Gaze Behaviors

To provide the impression that the peer is paying attention to and maintaining social engagement with the rider, we designed the peer to gaze at the rider from time to time as they are riding alongside each other. We programmed the peer to glance at the rider for a period of 0.25 seconds at intervals randomly drawn from the set of 3.0, 3.5, 4.0, 4.5, and 5.0 seconds.

When the peer is at an intersection, he or she should pay attention to traffic, find an appropriate target gap in traffic, and initiate crossing as the target gap approaches the intersection. Tracking traffic movement with head gaze is an effective way to convey attention to the stream of gaps.

The peer tracks traffic by selecting a car to follow as it approaches the intersection. The peer then continuously orients its gaze toward the car until it passes in front of the peer. To ensure that the peer tracks the target gap, the software checks to see if the lead vehicle of the target gap will be close to the intersection (i.e., within a specified distance, D) before the vehicle selected for tracking will pass the peer. If so, the peer will gaze down the road until the lead vehicle of the target gap is distance D from the intersection and then track it until it reaches the intersection. Otherwise, the peer tracks the selected vehicle and starts the process over again.

3.6 Synchronizing Reactive Simulation Motion Control with Action-Based Animation Behaviors

One of the challenges we faced with implementation of the virtual bicycle rider was the integration of motion control, on the simulation engine side, with the animation behavior on the Visualizer side. To facilitate the interaction between two parts of the system we designed a system of messages based on the gross motion of the virtual cyclist (acceleration and speed) to trigger transitions from one animation behavior to another.

The messages, labeled in Fig. 4 as M1, M2, and M3, were defined as follows:

- *M1 = {Virtual bicyclist's acceleration is greater than positive threshold};*
- *M2 = {Virtual bicyclist's acceleration is smaller than negative threshold};*
- *M3 = {The speed of the virtual bicyclist is zero}.*

Intuitively, we expect the rider to pedal in order to overcome inertia when accelerating. In order to ride at a constant speed, the rider must also pedal to compensate for drag (friction and air resistance forces). When decelerating at a rate greater than or equal to that caused by drag, we expect the rider to stop pedaling and either coast or brake. Thus, the peer should pedal when the acceleration produced by the active controllers is higher than the acceleration a_d due to the drag and should not pedal for lower accelerations.

If a_d is used as a threshold for the transition between pedaling and coasting, then there can be frequent switching between pedaling and coasting that looks unnatural. This dithering is caused by small fluctuations in acceleration near the drag threshold. To avoid such undesirable jittering, we introduced a small amount of hysteresis in the transitions by separating the boundaries for M1 and M2. Because a_d is negative, these boundaries are asymmetric relative to zero. Our current empirically determined heuristics use boundary values of $0.15\ \mathrm{m/s^2}$ for M1 and $-0.4\ \mathrm{m/s^2}$ for M2.

3.7 Modeling Traffic Generation at Intersections

Because accepted gap size is an important response variable in our experiments, we tend to think about traffic streams as streams of gaps and use the term *gap generation* instead of vehicle generation. In Hank, vehicles are typically injected into the simulation by special scenario control objects called *sources*. These objects provide a very flexible mechanism for generating well-structured streams of gaps and coordinating multiple streams [23].

In our experiments, it is critical to coordinate gap generation with the crossing behavior of the peer. The peer should cross specific target gaps of a prescribed size. We achieved this coordination by introducing an invisible "traffic light" object, which is controlled by the source that generates the stream of traffic passing through the intersection. The "traffic light" is seen by the peer, but is invisible to the participant and serves as a gate to the intersection for the virtual peer. When the source object determines it is time for the peer to cross, it changes the state of the invisible light to green or "go," allowing the virtual peer to enter the intersection. The state of the invisible light changes back to red or "stop," after the gap has passed by.

The vehicles in the simulation travel at a constant speed set by the source at the moment of vehicle creation. Therefore, the source can precisely compute the time of arrival to the intersection for each vehicle (or gap). To provide an extra level of flexibility, we introduced an additional parameter—time offset within the gap. This allows the experimenter to fine-tune where in the gap the virtual peer will attempt the crossing, thus, simulating crossing behavior that is more or less risky.

4 AN EXPERIMENT INVESTIGATING PEER INFLUENCES IN CHILDREN'S BICYCLING

We conducted a study to evaluate the effectiveness of our virtual peer system for studying social influences on children's bicycling behavior. The primary goal of the study was to determine whether watching a virtual peer engage in safe versus risky road-crossing behavior influenced children's own road-crossing behavior, both while they were riding with the peer and while they were subsequently riding alone. Children bicycled with the virtual peer for the first six intersections and bicycled alone for the last six intersections. At each of the first six intersections, children were instructed to first watch the peer cross the intersection and then to cross the intersection on their own. The peer chose a tight gap to cross in the Risky Peer condition and a large gap to cross in the Safe Peer condition. After crossing the sixth intersection, the peer said goodbye to the child and bicycled away. Children then crossed the last six intersections alone. The following questions were of particular interest:

1. *Did the peer's safe versus risky road-crossing behavior influence children's road-crossing behavior?*
2. *What was children's subjective experience of riding with the virtual peer?*

4.1 Study Design and Procedure

A Condition (risky versus safe peer) × Intersection Set (intersections 1-6 with peer versus intersections 8-13 without peer) design was used. The first factor was a between-subjects variable and the second was a within-subjects variable. Age and gender were counterbalanced across the two peer conditions.

The experimenter first helped children don a bicycling helmet and adjust the bike seat height. The experimenter then measured children's eye height while they were seated on the bike. This information was used to adjust the viewpoint for rendering images during the simulation. The experimenter informed the children that they would be riding through a virtual neighborhood and instructed them to ride as though they were riding in a similar, real-world neighborhood. The experiment began with a 3 to 5-minute warm-up period designed to familiarize children with the characteristics of the bicycle and the virtual environment. Children rode the bicycle on a straight, residential street with two intersections. During the warm-up period, there was no cross traffic at any of the intersections. Children were instructed to stay in the right lane and to stop at each intersection. The experimenter also asked children not to change gears on the bicycle. The familiarization session provided children with the opportunity to learn how to steer, pedal, stop, and start the bicycle.

Following the warm-up session, children met the virtual peer, who introduced him or herself and briefly explained the experiment procedure. As detailed in Section 3.2, the peer informed children that after they arrived together at each intersection, children would first watch the peer cross the intersection and then they would cross the intersection on their own. After the peer finished talking, the experimenter went over the procedure again to make sure the child understood the task.

Children rode through the first six intersections with the peer. There was no traffic on the street with the child and the peer, but there was continuous cross traffic on 12 intersections. The cross traffic was restricted to the lane closest to the participant and always approached from the participant's left side. The temporal intervals (gaps) between the cars were defined as the difference between the time at which the rear of the first vehicle reached the crossing line and the time at which the front of the second vehicle reached the crossing line. When the child and peer arrived at each intersection, they encountered three to four randomly ordered gaps of size 2.5, 3.0, 3.5, or 4.0 seconds followed by the target gap—the gap that the peer chose to cross. The gaps that preceded the target peer gap were always smaller than the target peer gap.

The peer always took a 3.5 s gap in the Risky Peer condition and a 5.5 s gap in the Safe Peer condition. Our choice of gaps for the risky and safe conditions was motivated by our previous work on child cyclists' gap choices [5]. In both conditions, the peer crossed through approximately the middle of the gap. This meant that the risky peer began to move 1.63 s before the rear of the lead car in the gap intersected with the crossing line (the peer's path through the intersection), leaving the peer with 5.13 s available for crossing. When the risky peer cleared the path of the oncoming car, there was 0.60 s left to spare. The safe peer began to move 2.81 s before the rear of the lead car in the gap intersected with the crossing line, leaving the peer with 8.31 s available for crossing. When the safe peer cleared the path of the oncoming car, there was 3.56 s left to spare.

Once the peer crossed the intersection, he or she waited on the other side for the child. The child then encountered a stream of gaps organized into logical blocks. Each block contained a random permutation of six different gap sizes: 1.5, 2.5, 3.5, 4.5, 5.5, and 6.5 seconds. Thus, the child saw all six gaps before any gap repeated. Once the child crossed the intersection, the peer resumed riding with the child.

After riding together for the first six intersections, the peer disengaged and the children crossed the last six intersections alone. At each of these intersections, children again encountered a stream of 1.5, 2.5, 3.5, 4.5, 5.5, and 6.5 s gaps organized into logical blocks with random permutations of the six gaps. Upon completing the riding task, children responded to a set of questions designed to gauge their subjective impression of the virtual peer. Their responses to these questions were audiotaped and transcribed verbatim for later coding.

4.2 Participants

A total of 27 participants completed the study: 14 ten-year olds (6 boys) and 13 twelve-year olds (5 boys).

4.3 Measures

We logged the position and orientation of all the dynamic objects in the simulation including all vehicles, the peer, and the participant for use in postexperiment data analysis. The key behavioral variables analyzed pertained to

Time 607.841 Frame # 13686 Bike x -454.77 Bike y -3.9 Bike speed -3.349

Fig. 5. A screenshot of the automatic data coding and after-action review tool. The visualization shows an abstract top-down view of the automatically coded rider's stopping position (red square), starting position (green square), the rider (pink square), and the peer waiting for on other side of the intersection (brown square). The front and back vehicles of the gap chosen by the rider are represented as blue rectangles in the crossing street.

1. stopping behavior,
2. gap choices,
3. starting behavior, and
4. time-to-spare.

The criteria evaluated on the nine-question subjective evaluation survey were as follows: appearance/realism, co-presence, overall animation fidelity of bicycle riding, social presence, attention to the peer, pedagogical benefits of the peer, and affect.

The quantitative measures such as the gaps chosen, the time-to-spare, and stopping and starting locations were automatically coded by a postexperiment program via analysis of the experiment log data. The program also featured an after-action review tool, which allowed experimenters to visualize the locations of stopping and starting positions, as well as the size of gaps taken and the time-to-spare. Experimenters could visualize the rider, peer, and vehicles at each intersection from the beginning to the end of the experiment in an abstract top-down view. In addition, the visualization displayed automatically coded variables including the rider's stopping location, starting location, speed, position, and orientation. A screenshot of the after-action review tool is shown in Fig. 5.

The rider's stopping and starting locations were automatically coded based on predetermined stopping and starting criteria. The criteria were established based on analysis of riders' stopping and starting behaviors from previous experiments involving solo riding by children and adults in the bicycling simulator.

The criteria were as follows:

- The stopping location was coded as the position nearest the intersection where the rider stayed below a speed of 0.1 meters per second for at least 2 seconds.
- If the rider came to a stop based on the criteria above, then starting location was coded as the

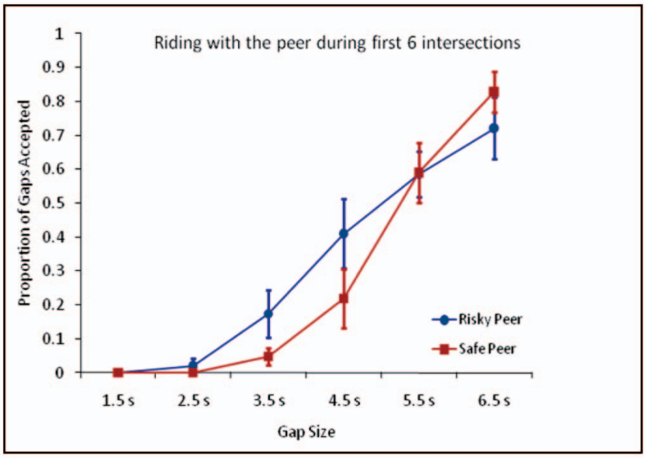


Fig. 6. The mean proportion of gaps of each size accepted by children at the first six intersection when riding with the peer.

location closest to the intersection where the rider accelerated above a speed of 1.0 meters per second.

- If the bicyclist never came to a stop based on the criteria above, then starting location was coded as the position where the rider consistently stayed above his/her slowest speed when accelerating to cross the intersection.

4.4 Results

4.4.1 Overview

The results are divided into four sets of analyses. The first analysis examines whether children's previous experience with the risky or safe peer influenced the likelihood that they came to a complete stop while they were riding alone. The second set examines whether the peer's road-crossing behavior influenced the size of the gaps children chose to cross. The third analysis examines whether the peer's road-crossing behavior influenced when children began to cross relative to when the lead car in the gap cleared the intersection (i.e., once the gap had opened). And the fourth set of analyses examines whether the peer's road-crossing behavior influenced the time-to-spare when children cleared the path of the oncoming car. In all of the analyses below, we analyzed the effect of the safe and risky peer separately for the first six intersections and the last six intersections. We did not examine age or gender effects due to the limited sample size.

4.4.2 Influence of the Virtual Peer on the Probability of Stopping at the Last Six Intersections

At the first six intersections, participants were required to come to a complete stop and wait for the peer to cross the intersection before proceeding. However, at the last six intersections, the peer was not there to provide the constraint that required participants to come to a complete stop. We compared the likelihood of coming to a complete stop at the last six intersections between children who had observed the safe peer and children who had interacted with the risky peer. Children who had observed the safe peer at the first six intersections failed to come to a complete stop at 22 percent (17/78) of the last six intersections they encountered. Participants in the risky peer condition failed to come to a complete stop at 44 percent (37/84) of the last six intersections they encountered. A chi-square analysis showed that this difference in performance was highly significant, $\chi^2(1,\ N = 162) = 9.012$, $p = 0.002$.

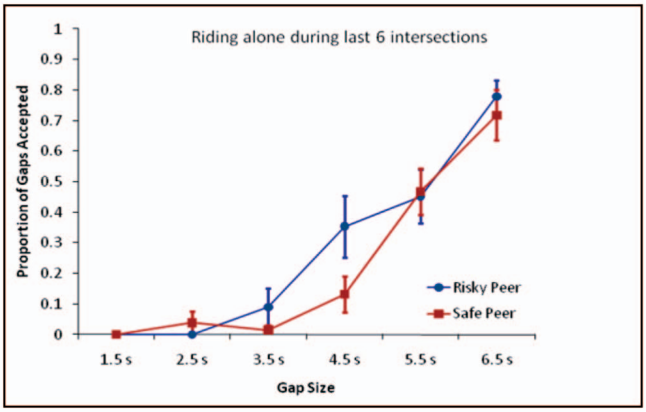


Fig. 7. The mean proportion of gaps of each size accepted by children at the last six intersections when riding without the peer.

4.4.3 Influence of the Virtual Peer on Gap Selection

How did the virtual peer influence the size of gaps participants chose to cross? Our first analyses of gap choice focused on the mean gap sizes chosen by children in the safe and risky peer conditions. Two one-way ANOVAs were performed with peer condition (risky peer versus safe peer) as the independent variable. One analysis was done for the intersections at which the peer was present, and one was done for the intersections at which there was no peer. When the peer was present, there was a marginally significant effect of peer condition, $F\ (1,\ 25) = 3.58,\ p = 0.07$, with children in the safe peer condition choosing larger gaps ($M = 5.8$ s, $SD = 0.34$) than children in the risky peer condition ($M = 5.4$ s, $SD = 0.62$). This effect was not present at the last six intersections, when the peer was absent, $F\ (1,\ 25) = 0.05,\ p = 0.82$.

Our second analysis of gap choice focused on the mean proportion of gaps of each size that children accepted. In other words, how often did children take gaps of a given size when they saw gaps of size 1.5, 2.5, 3.5, 4.5, 5.5, and 6.5. Figs. 6 and 7 show the mean proportion of gaps of each size that children in the safe and risky peer conditions accepted during the first six (Fig. 6) and last six intersections (Fig. 7). We conducted separate Condition (safe versus risky peer) × Intersection Set (first six versus last six) repeated measures ANOVAs for the proportion of 3.5, 4.5, 5.5, and 6.5 s gaps accepted. These analyses revealed a significant effect of condition for the 4.5 s gaps, $F\ (1,\ 24) = 4.34,\ p < 0.05$. Across the two intersection sets, children in the risky peer condition ($M = 0.38$, $SD = 0.38$) accepted a higher proportion of 4.5 s gaps than did children in the safe peer condition ($M = 0.17$, $SD = 0.26$). The effect of condition approached significance for the 3.5 s gaps, $F\ (1,\ 24) = 2.69,\ p = 0.11$, with children in the risky peer condition ($M = 0.13$, $SD = 0.25$) also accepting a higher proportion of 3.5 s gaps than did children in the safe condition ($M = 0.03$, $SD = 0.08$). The effect of condition did not approach significance for either the 5.5 or the 6.5 s gaps. Thus, children in both conditions almost always rejected the 1.5 and 2.5 s gaps, and usually accepted the 5.5 and 6.5 s gaps.

However, children in the risky peer condition were more likely to accept intermediate-sized 3.5 and 4.5 s gaps than were children in the safe peer condition.

4.4.4 Influence of the Virtual Peer on Initiating Road-Crossing Behavior

We also examined when children began moving relative to the rear of the lead car in the gap. This measure provides an index of how long it takes children to initiate crossing once the gap is available, defined as the temporal difference between the time at which the bicyclist began moving and the time at which the front vehicle of the target gap arrived at the crossing line (Negative times resulted in cases where children began to move before the rear of the lead car had reached the crossing line). We averaged these times across the first six and the last six intersections to create two scores for each participant. As before, separate one-way ANOVAs (one each for intersections with and without peer) were performed with peer condition (risky peer versus safe peer) as the independent variable. When the peer was present, there was a near-significant effect of peer condition, $F\ (1,\ 25) = 3.06,\ p = 0.09$, with participants in the safe peer condition starting to move sooner after the lead vehicle had passed ($M = 0.64$ s, $SD = 0.65$) than participants in the risky peer condition ($M = 1.1$ s, $SD = 0.59$). This effect was not present at the last six intersections, when the peer was absent, $F\ (1,\ 25) = 1.79,\ p = 0.19$.

4.4.5 Influence of the Virtual Peer on Time-to-Spare

Did the time left to spare between the bicyclist and the approaching car differ across the two conditions when children rode with the peer or alone? Time-to-spare was defined as the temporal difference between the time at which the bicyclist cleared the path of the oncoming car, and the time at which the rear vehicle of the target gap arrived at the crossing line. For each set of intersections, a one-way ANOVA was performed with peer condition as the independent variable. When the peer was present, there was no significant effect of peer condition, $F\ (1,\ 25) = 0.21,\ p = 0.65$, with an overall mean time-to-spare of 2.2 s ($SD = 0.94$). This was also the case at the last six intersections, when the peer was absent, $F\ (1,\ 25) = 0.04,\ p = 0.84$. The overall mean time-to-spare at the last six intersections was 2.9 s ($SD = 0.86$).

4.4.6 Qualitative Evaluation

In this section, we summarize the responses of the children to the postexperiment qualitative evaluation survey. On the appearance of the virtual peer, all children said that they thought that the peer was between 10 and 14 years old. The majority of the males thought that Alex was 10 years old, whereas the majority of the girls thought that Erin was 12 years old. Table 1 lists the questions that were administered to the participants in the postexperiment questionnaire.

TABLE 1
Postexperiment Questionnaire

1.	How old did you think Alex/Erin was?
2.	Safe riding is important; you should always watch out for cars and allow a large space to cross the street. Did Alex/Erin ride safely?
3.	If you were teaching Alex/Erin to ride, what advice would you give him/her?
4.	Do you think Alex/Erin was good at riding a bicycle?
5.	Was Alex/Erin a good example for how to ride your bike on busy streets?
6.	Does Alex/Erin remind you of someone you met before? If so, who?
7.	Were you happy to ride alongside Alex/Erin?
8.	What were the things you liked most about Alex/Erin?
9.	What were the things you liked least about Alex/Erin?

In response to how Alex/Erin rode, most of the participants said that the peer crossed safely through traffic. When asked about what advice they might give Alex or Erin, riders in both conditions responded that they often felt that the peer took small gaps and started to cross too soon.

Some sample responses include:

"Make sure it's a big gap."

"Be more careful about how much space you have between cars."

"Do not go toward the car that's coming, and wait, because the car could slam the brakes and stop, when she is right by it."

These responses are encouraging in that they attest to the potential pedagogical benefits of the virtual peer system for 10- and 12-year-old children. Training children to select safe gaps and to time their motion so that they leave a safe margin of time-to-spare is an important long-range goal of our research.

Responses to questions regarding the bicycling behavior of the peer suggest that the quality of the motion behaviors of the peer including starting, stopping, riding alongside, and pedaling were of reasonable visual fidelity. Overall responses from participants on questions regarding to what extent they would consider Alex or Erin to be good examples of riding behavior indicate that the virtual peer was a good model for learning, and that the participants paid attention to the peer crossing traffic at intersections. Overall, the responses of children suggest that the experience of riding with the peer for six intersections was fun and enjoyable. The following are a list of open-ended responses from children organized by content:

- Learning, setting a good example, attention to task:

  "I kind of took notice of how much space was between cars when she crossed so that I'd have an idea."

  "She showed me how to go across the street."
- Appearance and Personality:

  "She's a kid," "I like the Batman shirt, it was pretty cool."

  "She didn't talk very much; usually I ride with my sister or someone talking; She was friendly."
- Task related behaviors:

  "She always waited on the other side of the road instead of just keep going."

  "He waited for me; I could ride with him as he kept up with me and didn't go fast."

5 CONCLUSIONS AND FUTURE WORK

In this research, we created a virtual cyclist in an interactive, immersive bicycling simulator for the purpose of studying peer influences on children's road-crossing behavior. Our virtual peer framework provides a reliable, consistent, and adaptable platform for conducting behavioral research on peer influences on children. One of the contributions of the framework is a model of combining reactive motion controllers with animation action-based behaviors for a virtual human. The framework includes a model of complex interactions such as interpersonal social conversations, riding alongside another rider, traffic crossing behaviors, social and perceptual gaze behaviors, and bicycle riding behaviors for stopping, starting, pedaling, and so on.

As a platform to study the social influences on children's road-crossing behavior, the virtual peer system presented a consistent and controlled scenario for all trials to every participant. Informal observations and subjective responses of the participants suggest that the virtual peer appropriately interacted with participants, rode alongside them, took specified gaps in traffic, crossed them accordingly, rode using the appropriate actions (starting, pedaling, stopping, etc.), and said goodbye when appropriate.

The results of our study reveal several ways in which the riskiness of the peer's behavior had a significant effect on how children crossed intersections. Children who experienced the risky peer in the first six intersections were less likely to stop at the last six intersections than were children who experienced the safe peer in the first six intersections. An interesting trend was that children who rode with the safe peer tended to initiate crossing earlier in the gap than children who rode with the risky peer. Earlier initiation of crossing is typically associated with more mature road-crossing behavior [5]. The results also indicate that the risky versus safe behavior of the peer had an impact on children's willingness to cross 3.5 and 4.5 second gaps. These gaps are ambiguous in the sense that they are neither too small to cross nor are they easily crossable. Children who rode with a risky peer were more likely to cross these gaps than were children who rode with a safe peer.

Additional analyses revealed that across both conditions, children took smaller gaps when riding with the peer ($M = 5.5$ s, $SD = 0.65$) than when riding alone ($M = 5.8$ s, $SD = 0.40$), $\mathrm{F}(1, 25) = 6.27$, $p = 0.02$. The fact that children took smaller gaps during the first six than the last six intersections is inconsistent with our other work showing that children typically take smaller gaps at later intersections than they take at earlier intersections. This suggests that having the peer waiting on the other side of the intersection may have exerted some pressure for children to cross, leading to overall smaller gap choices. Together, these results provide strong evidence that the behavior of the peer had an influence on the behavior of the child rider both when riding with the peer and afterward.

In future studies, we plan to investigate the influence of factors such as the age (adult versus child) and gender (same versus cross) of the virtual peer cyclist on children's bicycle riding behavior in crossing busy intersections. Future work will also extend our virtual peer framework to include multiple virtual peer cyclists and virtual pedestrians who interact with the subject rider in order to evaluate the influence of group dynamics and pedestrian onlookers on the rider's traffic crossing behavior. Such additional work will provide much needed information about how peers influence children's road-crossing behavior, laying the groundwork for a comprehensive model of risk factors for childhood bicycling injuries.

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