Door and Doorway Etiquette for Virtual Humans

Wenjia Huang, *Member, IEEE* and Demetri Terzopoulos, *Fellow, IEEE*

Abstract—We introduce a framework for simulating a variety of nontrivial, socially motivated behaviors that underlie the orderly passage of pedestrians through doorways, especially the common courtesy of opening and holding doors open for others, an important etiquette that has been overlooked in the literature on autonomous multi-human animation. Emulating such social activity requires serious attention to the interplay of visual perception, navigation in constrained doorway environments, manipulation of a variety of door types, and high-level decision making based on social considerations. To tackle this complex human simulation problem, we take an artificial life approach to modeling autonomous pedestrians, proposing a layered architecture comprising mental, behavioral, and motor layers. The behavioral layer couples two stages: (1) a decentralized, agent-based strategy for dynamically determining the well-mannered ordering of pedestrians around doorways, and (2) a state-based model that directs and coordinates a pedestrian's interactions with the door. The mental layer is a Bayesian network decision model that dynamically selects appropriate door-holding behaviors by considering both internal and external social factors pertinent to pedestrians interacting with one another in and around doorways. Our framework addresses the various door types in common use and supports a variety of doorway etiquette scenarios with efficient, real-time performance.

Index Terms—Virtual humans, multi-human simulation, behavioral animation, social animation, door and doorway etiquette

1 Introduction

Autonomous virtual humans are finding broad applicability in the entertainment industry and beyond. Increasingly higher demands are being placed on their realism—not just the fidelity of their appearance and movement, but also their behavior and social interactions. This is evident in the lifelike non-player characters in several popular video game franchises such as "Grand Theft Auto", "Assassin's Creed", and "The Elder Scrolls". Most existing work on autonomous virtual humans addresses either reactive behaviors in the absence of social considerations (e.g., avoiding physical collisions), reactive behaviors partially affected by social interactions (e.g., eye contact during collision avoidance), or social behaviors with very loose motor interactions (e.g., gesturing during conversation).

Doors are ubiquitous impediments in our daily lives. Despite the large body of literature on human animation, computer graphics researchers have not yet given serious consideration to the common door as a mechanism that evokes not just complex body movements but also rich social interactions. Since the doorway is a shared resource, usually allowing just one person or perhaps two people to pass at once, it induces interesting social dynamics when several people wish to pass through from the same or from opposite sides. The related social rules, the customary code of polite behavior known as "door(way) etiquette", are broadly observed across different cultures.

Several different types of doors are in common use, each with particular interaction modalities, such as ordinary hinged doors, sprung hinged doors that open when pulled and/or pushed and close automatically when released, double doors that comprise two sprung hinged doors, and revolving doors. Using the sprung hinged door as an example, the social norm is to hold the door open for the convenience of others. Usually, a well-mannered person will hold the door open for someone following closely behind, or hold the door open in order to allow others to pass through the doorway first, as gentlemen will often do for ladies. However, these rules are not rigid—they will vary depending on dynamic factors related to a person's character and frame of mind, such as their kindness and their sense of haste, as well as the state of their environment, such as the distance of the follower. Door-holding behaviors are rich and may be somewhat unpredictable, hence they are of great interest in the context of human simulation and animation.

1.1 Tasks and Challenges

Even casual examination of real-world video footage (Fig. 1) reveals that interacting with doors involves nontrivial behavioral tasks. People approach the door in an orderly manner, avoiding collisions with others while observing precedence, attain a convenient location and orientation relative to the door, reach out for the door handle and pull the door open, and finally enter the doorway while perhaps holding the door open for others, or even stepping out of the way to allow a follower to pass through first.

The simulation task involves locomotion toward the door while avoiding collisions with other pedestrians and simultaneously determining a doorway passing order. The door

- W. Huang is with Houzz, Inc., Palo Alto, CA 94301. E-mail: catjiahuang@gmail.com.
- D. Terzopoulos is with the Computer Science Department, University of California, Los Angeles, Los Angeles, CA 90095. E-mail: dt@cs.ucla.edu.

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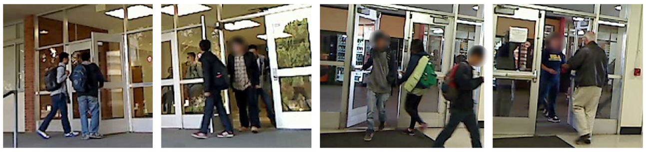


Fig. 1. Door and doorway etiquette in real life.

interaction task requires coordinated, collision-free door manipulations; i.e., locomoting while the upper body manipulates the door. Although the steering and door interaction tasks would at first seem to be unrelated, they must blend well for the resulting animation to appear natural. Moreover, there are additional interpersonal tasks. As one person is manipulating the door, the next person to pass through the doorway must at some point be established in a distributed manner subject to social norms, before that person can perform an appropriate follow through, including deliberately moving closer to the door while preparing to assume the door manipulation role. If doorway ordering takes place prematurely among pedestrians, the result will be unresponsive to situations in which, say, another person in a hurry cuts in and passes through next, or if doorway ordering occurs too late, the subsequent person may not act fluently.

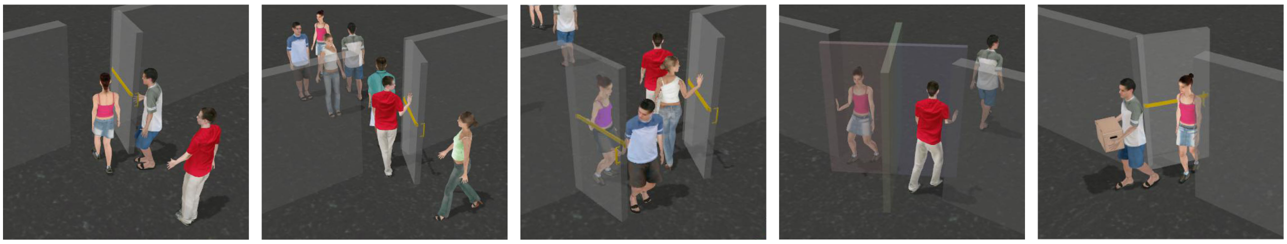
1.2 Contributions

The Artificial Life (ALife) approach to human simulation regards virtual humans from a decentralized, egocentric perspective, as autonomous agents, modeling them comprehensively at the motor, perceptual, behavioral, and cognitive levels [1], [2]. It has been successfully applied in whole or in part to multi-human simulation [3], [4], [5]. The ALife architecture can also support probabilistic decision-making and social interactions that require an awareness and consideration for others [6].

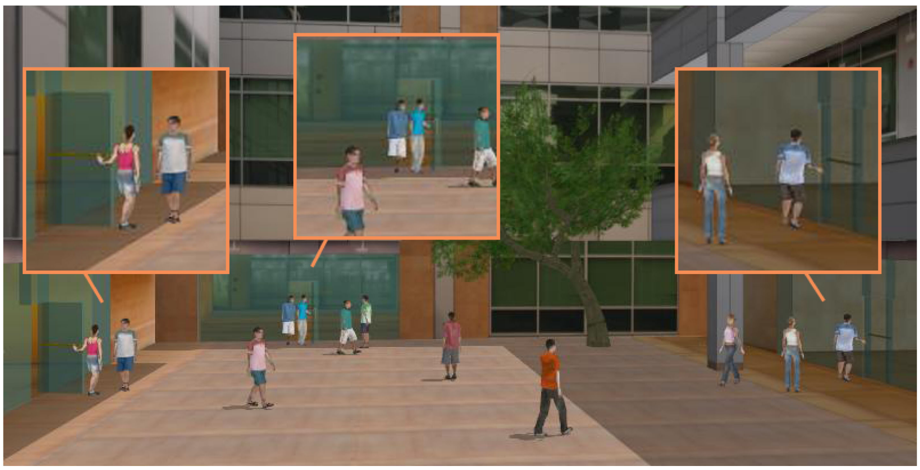
In this context, we introduce the first complete solution for simulating orderly, socially acceptable, multi-human behaviors subject to the rules of etiquette near doors and doorways (Fig. 2) [7]. Our innovative, agent-based simulation framework supports the decentralized perception of doors and other pedestrians in the vicinity of doorways, the design of orderly negotiation strategies for passing through doorways, and a state-based model for synthesizing versatile and stable door interaction driven by social considerations, which are encoded in the form of Bayesian networks that govern appropriate door-holding action selection under dynamic conditions.

Our layered and modular architecture enables easy and clean extensibility; for example, the support of various different doors—from single doors to double doors to revolving doors—and the simulation of more complicated doorway scenarios, including the introduction of pedestrians carrying objects, pushing perambulators, and friends walking shoulder to shoulder. To handle such scenarios, we augment the behavioral and/or motor layers of the characters, and easily incorporate additional social factors into their mental layers, without disturbing the prior implementation of other layers.

As we modify the type of door and its parameters, as well as the number and various types of pedestrians approaching the doorway, our multi-human simulation system can generate *completely automatically and in real time* a broad variety of convincing animations demonstrating proper door(way) etiquette, as shown in Fig. 2.



(a) (b) (c) (d) (e)



(f)

Fig. 2. Simulated door and doorway etiquette scenarios involving three common door types—a sprung single hinged door (a), (b), a sprung double hinged door (c), and a revolving door (d)—and involving a character carrying an object (e). (f) Real-time autonomous simulation of a multiple-door scenario with 4 doors and 16 pedestrians.

1.3 Overview

The remainder of the paper is organized as follows: Section 2 reviews related work. Section 3 summarizes our framework. Section 4 presents the technical details of the behavioral synthesis underlying doorway ordering and door interactions among pedestrians. Section 5 presents the decision model and constituent factors that determine behavior generation in our autonomous pedestrians. Section 6 presents our experiments and results. Section 7 concludes the paper and discusses avenues for future work.

2 Related Work

The topic of human behavior around doors and doorways has been addressed only casually in the graphics literature, and there exists some partially relevant literature from psychology and robotics/AI.

2.1 Agent-Based Multi-Human Simulation

As opposed to "crowd simulation", where the motions of multitudes of simple human characters are typically visualized from a distance, our work on doorway etiquette makes a much needed contribution to autonomous agent-based, multi-human simulation (see, e.g., [3], [4], [5]). This is an endeavor whose objective includes the automatic animation of the *detailed* socially-motivated behaviors of smaller groups of people in urban environments. Although detailed body kinematics, locomotion, perception, reactive behavior, and cognition are dealt with in a distributed, agent-centric manner, the collective exhibits the natural characteristics of human crowds, as is the case in the real world. In this context, some recent work has incorporated psychological models for generating diverse steering behaviors [8], [9] as well as probabilistic decision models for emulating complex social behaviors [6]. In principle, agent-based models are amenable to extension with additional behaviors that support doorway etiquette, but this is by no means easy to achieve in practice.

By contrast to our ALife approach, data-driven approaches have been used to model human behaviors, particularly in the context of crowds. For example, Lemercier et al. [10] developed crowd following behaviors by analyzing motion capture data whereas Flagg and Rehg [11] synthesized steering behaviors by tracking pedestrians in videos of natural crowds. Such data-driven approaches do not yet appear useful in tackling the more complex behavioral and social modeling tasks that we address with our ALife approach.

2.2 Relevant Psychological Theories

At the highest level, our work is informed by psychological findings, although there is a dearth of quantitative psychological research on specific human social behaviors around doors. Based on data analysis, Santamaria and Rosenbaum [12] proposed a shared-effort model and studied two factors that could influence door etiquette. They found that close proximity between pedestrians yields a higher probability of holding the door open regardless of the number of followers; thus, we include the effort factor in our model. The influence of gender in door holding—that holders offer courtesies to females more frequently than to males—is also quantifiable [13]. Finally, personality and emotion [14] are commonly used to model transient (e.g., urgency) and non-transient (e.g., kindness) human mental states.

2.3 Multi-Character Interactions

Generating motions around doorways requires cooperative movements between multiple characters. On the motion level, graphics researchers have focused on the animation of interactions between multiple human characters [15], [16], exploring motion analysis and synthesis approaches to achieving cooperative multi-character movements, among them physically-based optimization [17], and motion editing [18]. Lau and Kuffner [19] deal simultaneously with steering behaviors and some simple reactive behaviors by building an abstract state-space, which facilitates motion planning and modification. Their work has inspired us to develop a state-based model to deal with the complex door interaction and cooperation tasks that arise as people coordinate themselves to pass through the door; however, we must also take into account the fact that people exhibit diverse behaviors driven by perception and social norms in the presence of others.

Some doorway passing ordering tasks for crowds have been approached through proxy agents [20] and situation agents [21] that provide influence over other agents such that they can cooperate in order to pass through openings more efficiently, but these efforts ignore the existence of door mechanisms and the potentially involved manual interactions with them that form an important aspect of door etiquette. Kallmann and Thalmann [22] adopted scripting techniques to model multiple characters passing through open doorways. Based on the motion analysis of people approaching and opening doors [23], prior work includes highly limited results involving hinged [24] and revolving [25] doors, but aside from collision avoidance, the rich social interactions mediated by doors and doorways have thus far been disregarded. Doorway behaviors are relevant to simulating social territoriality, by incorporating social norms into rules governing individual positioning and orienting in small groups and socially-aware movement in tight spaces [26], [27].

2.4 Planning Actions and Robotics

In the domain of Artificial Intelligence, the problem of planning in the real world considers both scheduling constraints (e.g., timing of motions) and resource constraints (e.g., doorways allowing only a limited number of agents to negotiate at the same time) [28]. More specifically, the problem of people holding doors or collaborating to pass through doorways in various ways resembles the multi-agent planning problem [29]. Through symbolic reasoning, these methods can dynamically generate plans to execute a task, but symbolic action generation fails to account for the inherent constraints and coordination required at the motion generation level, which largely ignores the complexity of the problem at hand.

On the motion level, the door manipulation problem has been investigated in the robotics literature [30], [31], [32], albeit focusing on enabling individual robots to open doors and mechanically pass through them in a non-human-like manner.

3 Framework

Fig. 3 presents an overview of our framework. When we assign to a pedestrian a target goal that lies on the far side

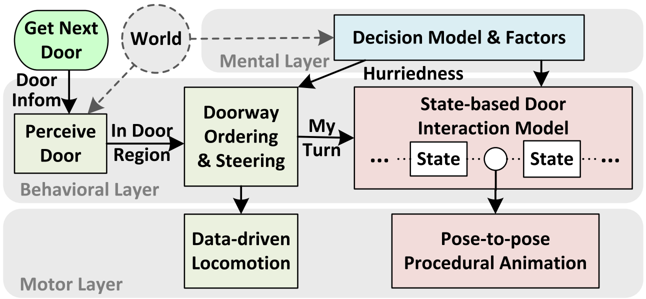


Fig. 3. Our system comprises two phases, (i) perceiving and approaching the door (green) and (ii) interacting with the door (red). A high-level factor and decision model governs both phases (blue).

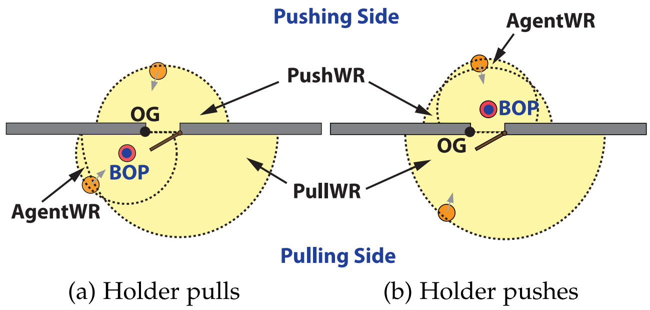


Fig. 4. (Overhead view) The Best Open-door Position (BOP) is the position the holder should approach and stop at in order to manipulate the door. Its positions are defined differently in the door-pulling (a) and door-pushing (b) cases. The Opposing Goal (OG) is the position toward which the follower from the other side should proceed and wait. The Pushing-side Waiting Region (PushWR) is a circle around the door center that prevents the pushing-side follower from advancing too close to the door and blocking the pulling-side holder. The Pulling-side Waiting Region (PullWR), centered at the door hinge, maintains the distance of the pulling-side follower from the door hinge, thus preventing collision with the door panel when the door is open. The Agent Waiting Region (AgentWR) is a circle centered at the holder, which prevents the follower from approaching too closely to the holder.

of a doorway, the pedestrian will first engage in global path planning to determine whether it must pass through a doorway. Following [3], the environment of the autonomous pedestrians is abstracted as a 2D gridmap that encodes the locations of static obstacles, in our case the walls, as well as the positions of dynamic obstacles; i.e., other pedestrians. When a pedestrian wishes to pass through a doorway, it will observe the door and approach employing its steering/locomotion system. If the pedestrian perceives other pedestrians ahead, its behavior model will dynamically establish a doorway-passing order. When the pedestrian's turn comes, its state-based door interaction model is enabled and it is supported by a lower-level pose-to-pose procedural animation system. A high-level decision model influenced by psychological factors determines door-holding behavior during the door interaction phase and it affects the passing order during the doorway phase. After passing through the doorway, the pedestrian will walk away, avoiding collisions with oncoming pedestrian traffic.

4 Behavioral Synthesis

As our behavioral model for doorway ordering and door interaction are interconnected, we present their details together in this section. For simplicity, we will use the most common sprung single hinged door in our technical description, and then generalize our methods to other door types, including the revolving door and the double door.

4.1 Real-World Video Study

To study the behaviors of pedestrians around doors, we recorded 3 videos, each around 20 minutes long, during business hours around two major doorways of Boelter Hall on the UCLA campus (Fig. 1). The recorded pedestrian traffic flows varied significantly, including dense flows between classes and sparse flow during classes, which captured a variety of usage patterns. We perused the videos, performing an informal, nonquantitative analysis of their content, which subsequently informed the development and implementation of our model.

In general, the videos reveal a variety of nontrivial locomotive, behavioral, and social phenomena around doors that must inevitably be addressed by our model. Most significantly in this case, we observed that doors are often held open by pedestrians for others approaching the doorway from the same side as well as for visible pedestrians approaching from the opposite side of the transparent doors. Collective behaviors were also observed, including same-side flows with sequential door holding among pedestrians and, in the case of double doors, nontrivial dynamic balancing in the use of both doors.

Note that we develop our model under the assumption that doors are transparent, affording pedestrians full perception of activity on the opposite side of a doorway.

4.2 The Doorway and Doorway Ordering

When the pedestrian enters the doorway region, it will prepare to pass through the doorway using an agent-based doorway ordering process. This decentralized process enables the pedestrians to order themselves dynamically and adapt naturally to unexpected changes in their perceived environmental situation. For example, if a pedestrian in a hurry cuts in front of others, they can adapt by giving way.

Perusing our real-world videos, we determined that there are typically two roles in interacting with a sprung single hinged door—"door-holder" (or simply "holder") and "follower". The holder is the pedestrian that is interacting with the door, and the follower is a pedestrian that will pass next, behind the holder. In addition to these two roles, a pedestrian that has not participated in door interaction will find another pedestrian to follow, and regard it the "leader". The follower is subject to change up to the time that the holder has opened the door about half-way, and can then either continue to hold the door or simply release it. This is considered the "critical motion phase" of the state-based door interaction model described in Section 4.3. When the holder reaches the critical motion phase, any pedestrian considers the holder as the leader will commit as a follower and pass through the doorway next.

Pedestrians should wait in sensible positions so as not to impede others currently passing through the doorway. We define several waiting regions as shown in (Fig. 4), whose measurements for various scenarios are specified in Table 1. If the holder is situated on the pulling side of the door, its follower on the same side should stop if the follower enters the doorway $\mathrm{Region}(\mathrm{PullWR} \cup \mathrm{AgentWR})$, and its opposing-side

TABLE 1
Measurements of the Door Waiting Regions (WRs) for Different Situations (in Meters)

	PullWR	PushWR	AgentWR
Simple Door	3.3	2.5	1.5
Revolving Door	3.0	3.0	1.5
Double Door	3.5	2.5	1.5

The waiting regions for the double door are centered at the centers of the two sprung single hinged doors.

follower should stop if the follower enters $\mathrm{Region(PushWR)}$. If the holder is situated on the pushing side of the door, the corresponding waiting regions are $\mathrm{Region(PushWR \cup Agent\ WR)}$ and $\mathrm{Region(PullWR)}$. If there are multiple pedestrians waiting on one side, each pedestrian must wait behind its self-selected leader, typically by defining $\mathrm{AgentWR}$ for its leader.

More specifically, in sprung single hinged door case, the ordering algorithm works as follows (Figs. 5a and 5b): Each pedestrian will sense its environment, identify all pedestrians to the front (on the same side of and closer to the door), and choose the closest pedestrian as "initial leader". Subsequently, the leader selection process proceeds according to Algorithm 1 to adjust the leader if appropriate after considering the situation within the sensing range. In this algorithm, "compete" means to determine if any other pedestrians are more proximal to the leader (with proximity evaluated according to the distance to the leader and waiting time $E(d_{\mathrm{leader}}, t_{\mathrm{wait}})$) and, among those pedestrians that are more proximal than me, choose the least proximal one as the new leader. The main idea behind the algorithm is that people need to evaluate the passing order more carefully when they are likely to pass soon (in which case their initial leader is the holder or a follower). After a pedestrian's leader is resolved using Algorithm 1, the pedestrian will decide its doorway behavior according to Algorithm 2. These algorithms are applied at a rate of 30 fps, which affords flexibility to followers until the holder enters the critical motion phase.

Algorithm 1. Leader Selection

if *I have an initial leader and any other pedestrians on the same side of the door choose the same initial leader* **then**
  compete with pedestrians on the same side of the door and select a new leader
  if *the new leader is a follower or holder* **then**
    compete with pedestrians on the opposite side of the door to choose the leader
  end
else if *I have no initial leader and there is an opposing follower/holder* **then**
  choose the opposing follower (or holder if follower is not available) as initial leader, and compete with other pedestrians on the opposite side (if any, and who may also choose this initial leader) to choose the leader
else
  designate the initial leader as the leader, or choose no leader if there is no initial leader
end

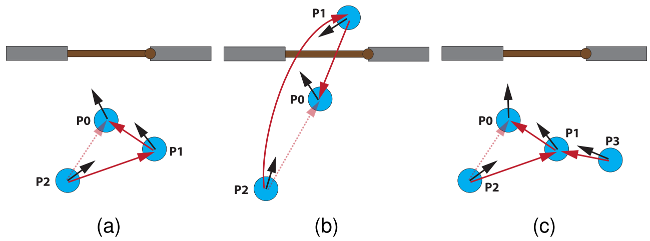


Fig. 5. Agent-based doorway ordering process (overhead view) (assuming no effect from waiting time). (a) P_2 initially selects P_0 as leader, but then switches to P_1, since P_1 is closer to P_0. (b) In the case of a transparent door, P_2 switches its leader from P_0 to P_1 since P_1 is closest to P_0. (c) It is possible for two pedestrians, P_2 and P_3, to have the same leader P_1.

Algorithm 2. Decide Doorway Behavior

if *I have chosen a leader* **then**
  if *the leader is a holder and has entered the critical phase* **then**
    commit to being a follower and approach the leader until close enough to the door (having entered either PullWR or PushWR), and then initiate the door interaction model
  else
    if *the leader is on the same side* **then**
      approach the leader
    else
      `/* leader is on the opposite side */`
      approach the door
    end
  end
else
  `/* I have no leader */`
  if *I am sufficiently close to the door* **then**
    assume the role of holder and initiate the door interaction model
  else
    approach the door
  end
end

Note that it is still possible for two pedestrians to choose the same leader (Fig. 5c), as can happen in reality. This is fine while following the leader, but a conflict will ensue if both followers trigger the door interaction model. A mutex prevents more than a single pedestrian from simultaneously initiating the door interaction model. This corresponds to the natural situation that if one person observes another person initiating a door interaction first, they will abort their own intention to interact with the door and re-plan based on the new situation.

4.3 State-Based Door Interaction Model

We approach the problem of synthesizing motions that support multi-character interactions with doors based on the general ideas of [19], who synthesize motions based on abstract behavior models with states. They associated each state with a set of candidate segments of motion data, and the resulting motion is synthesized on-line while the characters interact with their environments.

To satisfy the need to generate highly constrained full-body motions in the narrow doorway environment, we implemented a custom procedural motion model with

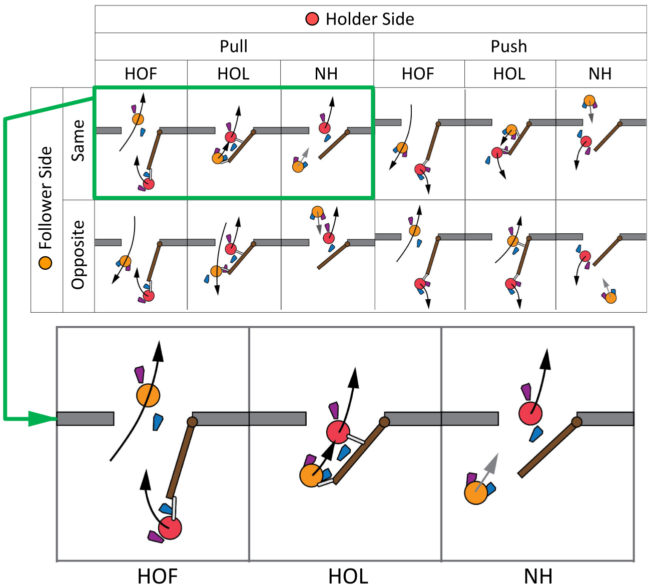


Fig. 6. All possible door-holding behaviors (overhead view) for a holder (red) with a follower (yellow). From left to right, holding the door for the follower to pass first (HOF), holding the door for the follower to pass later (HOL), and not holding the door (NH). holder behaviors on both the pull and push sides of the door with a follower approaching either from the same side or from the opposite side of the door are illustrated.

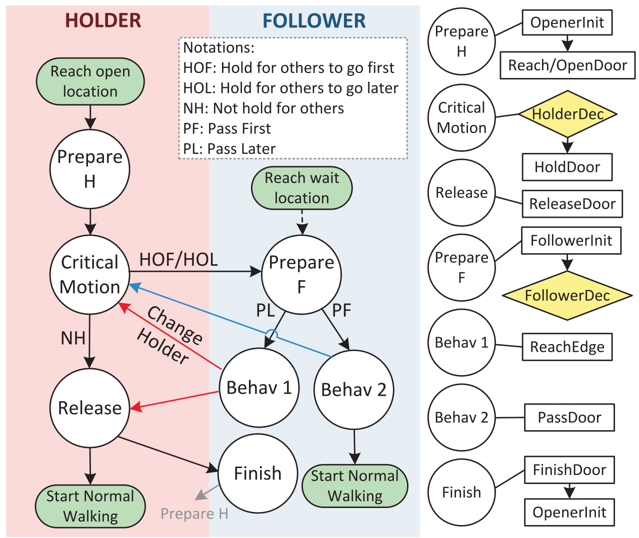


Fig. 7. The state-based model for door interaction. The diagram shows an overview of the interactions between holder and follower, as well as a detailed view of the specific state(s) of the motion phases implemented in each interaction routine. Circles represent interaction states. Squares represent states of motion phases. Diamonds represent decision states in which pedestrians will choose different door-holding behaviors or following behaviors. Ovals represent states in which pedestrians will switch between data-driven locomotion and the procedural motion model. A follower can become a holder by virtue of the (red) HOLDER routine, at which point a PL follower takes control of the door, then the holder releases the door and the follower becomes the new holder. A HOF holder can continuously hold the door for another pedestrian to pass through, according to the (blue) FOLLOWER routine.

Inverse Kinematics (IK) (see Appendix C), together with a compatible design of the door controller (see Appendix A), which can robustly support our state-based model.[1]

The door-holding procedure is based on discretized motion steps, which enables collaboration in passing control of the door among multiple pedestrians. The door is considered the core component of the procedure, which implicitly guides and sets constraints during the interaction process. We identify and divide the states based on critical motion points viewed from the video that are important in synchronizing cooperative motions between the holder and follower. Subsequently, transitions are added to enable the interaction.

In sprung single hinged door case, Fig. 6 illustrates the possible door-holding behaviors for a holder with a follower. Fig. 7 details the structure of our state-based door interaction model. Appendix B describes its primary states and associated key poses.

4.4 Attention-Driven Head/Eye Motion

Head and eye movements are critical to realistic social behavior [33], [34]; thus, we have included an attention-driven Head/Eye system whose details are presented in [7]. Since in our recorded real-world videos we observed specific head/eye motions in the following situations in the context of the door-holding task, our system automatically synthesizes them accordingly:

- Pedestrians pay visual attention to their manipulating-side hand to locate the handle of the door in order to reach it with their hand.
- If they are considerate, they will voluntarily rotate their heads back to check if another character is following and, if so, hold the door. While the follower is passing through the doorway, the holder will look at the follower.

1. Data-driven methods can potentially be incorporated into our framework at this level, so long as they support the abstraction of actions (states).

4.5 Other Door Types

Our door behavior synthesis framework can accommodate door types other than the sprung single hinged doors, including revolving doors and sprung double hinged doors. Our system is readily extensible by simply modifying one or more behavioral components in the framework of the sprung single hinged door.

4.5.1 *Revolving Door*

A typical revolving door comprises 4 panels and a person can push one of them to pass through the doorway. The door control is modeled in 4 phases (Fig. 8a), and it provides an additional function to identify the best entry phase for either side of the door given its current rotation (angle).

An important feature of the revolving door is that people entering the doorway from both sides can interact with

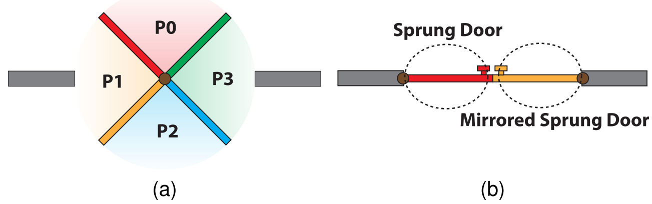


Fig. 8. (a) Revolving door design with 4 phases. (b) Double door designed as two juxtaposed sprung single hinged doors.

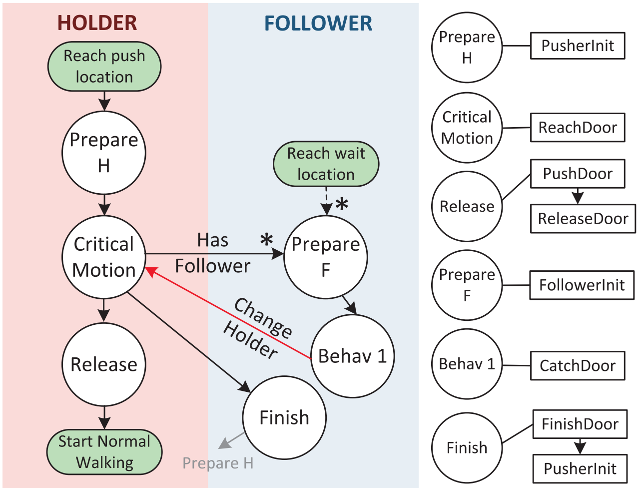


Fig. 9. Revolving door adoption of the state-based door interaction model. Two "$*$": if the follower is on the same side, the *Prepare F* state needs to wait after the *Critical Motion* state of the holder. If the follower is on the opposite side, the *Prepare F* state can start as long as the follower has reached the wait location.

the door at the same time. Usually one person will initiate the motion and the door can accommodate up to 2 followers at the same time, one from the same side and one from the opposite side. The opposite side follower can start the door interaction at any time without needing to wait until the pusher (holder) has completed the critical motion, whereas the same side follower needs to wait, which is similar to the sprung single hinged door situation when holding the door for others to pass later. These characteristics necessitate partial alterations in both doorway ordering and door interaction.

Regarding doorway ordering, we allow up to 2 holders and 2 followers at the same time. Pedestrians will prefer to select a leader from the same side. Subsequently, we allow at most 2 door interaction models running at the same time, each of which deals with a pair of interactions between one holder and one follower. Initially no one is handling the door, and one pedestrian will be the initial holder with at most 2 followers; as the system runs, the opposite side follower will become the holder and will choose its own follower, potentially from the same side; thus 2 door interaction models are now running simultaneously. As there is only one possible behavior of pushing and passing through the door, this yields a simplification of the door interaction model (Fig. 9). On the motion level, extra effort is placed on enabling the follower to catch up to the moving door and time a suitable entry point. Interesting behaviors emerge, such as in the case where the pedestrian cannot catch up and must wait for the subsequent door opening.

4.5.2 *Double Hinged Door*

The double door introduces a most interesting scenario for doorway etiquette as it presents two doors from which to choose. In North America, people will prefer to pass through the right-hand door. However, this is not compulsory. An interesting phenomenon we observed from video is that, if there is a holder, the follower will tend to choose the held door, regardless of whether it is the right or left door. Moreover, if either door becomes congested with traffic, the other door will be put to use. To simulate both phenomena, at the doorway behavior level, pedestrians must observe the traffic loads of both doors.

The door control and door interaction model is simply a composition of two sprung single hinged doors, one a mirror image of the other (Fig. 8b), and there is no need for modification. The major modification is in finding the leader (Algorithm 3).

Algorithm 3. Leader Selection (Double Door Case)

if *there is no same-side pedestrian closer to the door than me* **then**
  get possible leader by considering opposite-side pedestrians (Algorithm 4)
else if *there is one same-side pedestrian before me* **then**
  choose this pedestrian as initial leader and modify the leader by considering opposite-side pedestrians (Algorithm 4)
else if *there are two same-side pedestrians before me* **then**
  choose an initial leader
  if *I have not arrived within the waiting region* **then**
    take the initial leader as the leader
  else
    modify the leader by considering opposite-side pedestrians (Algorithm 4)
  end
else
  `/* more than two same-side pedestrians */`
  choose an initial leader and designate it the leader
end

Since the double door requires additional consideration on choosing a passing side, doorway behavior generation needs to take this into account. The leader selection procedure involves an extra procedure, Algorithm 4, for modifying the potential leader by considering opposite-side pedestrians and simultaneously choosing the passing side, under the condition that no more than 2 same-side pedestrians are closer to the door. The initial evaluation in the algorithm for determining whether there is any other pedestrian prior to me is based on $E(d_{\text{leader}}, t_{\text{wait}})$. The algorithm will return either a leader or the selected passing side. If a leader is returned, the pedestrian will adopt the leader's passing side. Finally, the doorway behavior is decided according to Algorithm 2.

4.6 Other Behaviors

Our door behavior synthesis framework is readily extensible to support more complicated scenarios. Carrying a big box or pushing a perambulator while trying to open a door and pass through the doorway is a challenge. However, since our framework largely separates the behavior and motor layers, the task boils down to supplementing the set of skills in the motor layer. It is rather easy to support the motor skill of carrying a box. Consider the skill of manipulating a perambulator. This requires a motion controller. We have crafted a procedural motion model with control functions to work properly in conjunction with our pose-to-pose procedural animation system. Additionally, it becomes necessary to expand the doorway regions to support the new doorway behaviors. (a scale of 1.2 is applied to the values of simple door case in Table 1)

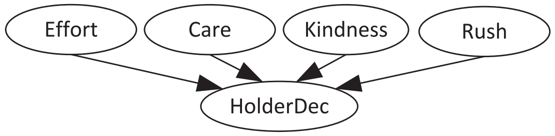


Fig. 10. Bayesian network for holder behavior decision-making.

Algorithm 4. Leader Modification (Double Door Case)

if *there is no opposite-side pedestrian prior to me* **then**
  if *I have an initial leader that is already a follower/holder, or no door is free* **then**
    take the initial leader as the leader
  else
    prefer the free door, if any, rather than the right-side door.
  end
else
  `/* an opposite-side pedestrian is prior to me */`
  if *my initial leader is a follower/holder and I rank third among same-side and opposite-side pedestrians* **then**
    if *there is a free door* **then**
      choose the free side
    else
      take the opposite-side pedestrian as the leader, which is prior to me
    end
  else
    if *I have an initial leader* **then**
      take the initial leader as the leader
    else
      take the the opposite-side pedestrian as the leader, which is prior to me
    end
  end
end

Interesting scenarios that involve personal connections between pedestrians can be readily simulated by augmenting the doorway behavior module. The modifications relate to deciding doorway behavior (modifications of Algorithm 2), while the perception and the leader selection procedure remain unchanged. In scenarios of a follower overtaking a leader to offer door-opening assistance, the follower will walk at an increased speed toward the door instead of toward the leader, ultimately resulting in the follower becoming the leader by virtue of dynamic doorway ordering. In scenarios of friends designated as such and walking together, shoulder to shoulder, no matter who is the leader or follower, both will walk toward the door while adjusting their speed and proximity to accommodate one another, resulting in an improvisational passing order.

5 Social Factors and the Decision Model

Different people will have differing behaviors in the same situation. We adopt a probabilistic model for decision-making in the context of door-holding behaviors, which is inspired by the work of Yu and Terzopoulos [6]. In particular, we build a Bayesian network to decide door-holding behaviors (Fig. 10 with Table 2). Unlike the prior work, our Bayesian network makes its decisions based on the probability rather than a utility. From the modeling and computational perspective, it gives equally sound results. There are four random variables or factors in the network. The value of each variable is between 0.0 and 1.0, with *Effort* and *Care* evaluated dynamically at runtime, while *Kindness* and *Rush* are statically assigned from the start. We discuss these social factors next.

TABLE 2
Conditional Probability Table (CPT) for the Door-Holding Behavior Decision Network

Rush = T						Rush = F					
Effort	Care	Kindness	HOL	HOF	NH	Effort	Care	Kindness	HOL	HOF	NH
T	T	T	0.7	0.1	0.2	T	T	T	0.2	0.8	0.0
T	T	F	0.6	0.1	0.3	T	T	F	0.7	0.2	0.1
T	F	T	0.7	0.0	0.3	T	F	T	0.9	0.1	0.0
T	F	F	0.5	0.0	0.5	T	F	F	0.6	0.1	0.3
F	T	T	0.1	0.0	0.9	F	T	T	0.2	0.1	0.7
F	T	F	0.1	0.0	0.9	F	T	F	0.5	0.0	0.5
F	F	T	0.1	0.0	0.9	F	F	T	0.3	0.0	0.7
F	F	F	0.0	0.0	1.0	F	F	F	0.1	0.0	0.9

(Each value in the CPTs is chosen by experience under each condition, a combination of binary settings for all 4 factors.)

5.1 Social Factors

5.1.1 Effort

Based on the study of Santamaria and Rosenbaum [12], the door-holding problem is regarded as a minimum shared-effort model. As a person holds the door open for someone else, others will tend to hold the door open for this person at other times. Therefore the total energy any person expends in passing through doors will be minimized. In their study, these researchers found that the closer the distance from the follower to the holder, the larger the probability of holding the door, regardless of whether there are 1 or 2 followers. Thus, we incorporate a *Effort* factor, which describes how beneficial it is to hold the door for others in the current situation. The *Effort* factor is dynamically evaluated as a function of the current distance d to the follower. For $d < 1.0\ \mathrm{m}$, the function value is 1.0; for $d > 4.0\ \mathrm{m}$, the value is 0.0; for $1.0\ \mathrm{m} \leq d \leq 4.0\ \mathrm{m}$, the function value is linearly interpolated between 1.0 and 0.0.

5.1.2 Care

Gender differences are significant in doorway etiquette. In many cultures, gentlemen would, in most cases, prefer to hold open the door for ladies, a phenomenon which was studied by Webster et al. [13]. Therefore, we include a *Gender* factor that takes into account the gender of the follower. In most cultures, people would offer to open the door for those who need assistance; e.g., when carrying an object. Therefore we include a *Carrier* factor that indicates whether or not the follower is carrying an object. Hence, we introduce a *Care* variable to encode how much the follower is assessed to require assistance. It is accessed from the *Gender* and *Carrier* factors, per the sub-network shown in Fig. 11 with the CPT in Table 3.

5.1.3 Personality and Emotion

Personality determines the coherent psychological state of people, while emotion represent the temporary mental state

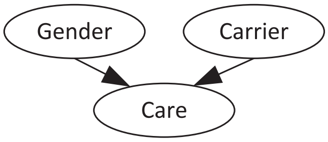


Fig. 11. Bayesian network for determining the value of the variable *Care*.

of people [14]. They can result in completely different behaviors in the same situation. The Big 5 model [35] systematically factorizes personality into five factors, with "agreeableness" representing one's helpful nature, reflecting kindness. Thus we include a *Kindness* factor to determine whether a character is willing to hold the door for others. If people are in a rush, they will tend to hold the door open less frequently, since door holding takes extra time and causes delay, which can be critical in hurried situations such as building evacuations. We introduce a *Rush* factor that regulates how hurried the holder is.

5.2 Decision Model for Door-Holding Behaviors

Given the above variables, the structure of the network is shown in Fig. 10. Its output comprises the 3 different holding behaviors (actions), which include holding the door for others to pass first (HOF), holding the door for others to pass later (HOL), and not holding the door (NH). Given all the values for the factors of the current state, the decision network will calculate the probabilities (utilities) of all the actions, and the action with maximal probability will be chosen in accordance with the Maximum Expected Utility Principle (MEU) (see [36], Chapter 16.5).

5.3 Settings and Updates

Values for *Effort*, *Gender* and *Carrier* will be acquired from the dynamic state of the environment, while *Kindness* and *Rush* will be initially assigned to each person. The Conditional Probability Tables (CPTs) (Tables 2 and 3) for setting the network are designed based on heuristics gleaned from our experience.

The *Rush* factor is also used to vary the speed of pedestrians in the doorway. A rushed pedestrian is able to walk faster and possibly surpass pedestrians not in a rush, which results in quicker passing. A pedestrian is also able to walk faster, but in order to open the door for others when noticing others' need for assistance, in which case *Rush* = 1.0. Additionally, another important social trait that we added is for the follower to speed up if it is too far from the holder.

6 Results

Our efficient model is capable of real-time performance. Our simulator runs on a 3.33 GHz Intel Xeon computer with 12 GB memory and an NVIDIA Quadro FX 4,800 graphics card.

TABLE 3
CPT for the *Care* Network

Gender	Carrier	Care
Female	T	1.0
Female	F	1.0
Male	T	1.0
Male	F	0.0

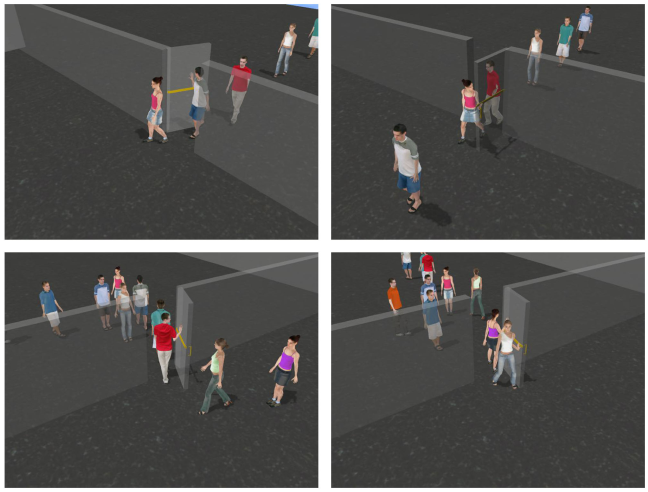


Fig. 12. Sprung single hinged door scenario simulations.

In a 4-door, 16-pedestrian scenario, with the simple door type, the performance is about 50 fps including rendering. Integrated with the building model shown in Fig. 2f, the performance falls to about 25 fps as the geometric complexity of the models dominates the simulation time. As we run our simulation system, the pedestrians will autonomously walk toward their destinations, passing through one or more doors and performing door manipulation/holding behaviors as necessary. Flying the virtual camera through the environment, we observe the evolution of a highly dynamic, socially meaningful process as pedestrians approaching a door encounter other pedestrians. They competently sort out their doorway passing order while showing concern for one another. If pedestrians that arrive at their destinations are reset back to their initial states, the simulation can run indefinitely, continually producing a variety of non-repetitive human interactions in and around the doorways.

Next, we will present results of 3 different types of doors with the sprung single hinged door serving as the baseline case. Appendix D presents a user survey that we conducted to validate the realism of our simulations with different social factor settings.

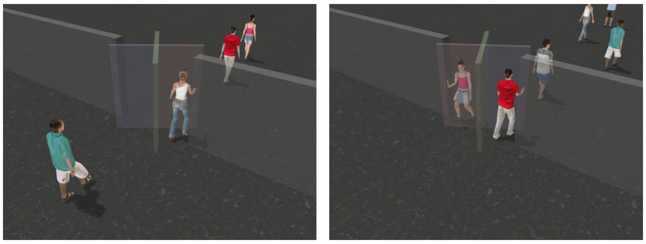
6.1 Sprung Single Hinged Door Scenario Simulations

Our system can synthesize multiple characters passing through a sprung single hinged door in a continuous manner, while generating cooperative door manipulation and holding behaviors between them (Fig. 12). It can generate same-way door passing behaviors, both from the pull and push sides of the door (Fig. 12 top), and opposing-way door-passing behaviors (Fig. 12 bottom). Different holding behaviors are generated and paired with corresponding following behaviors, and they are well-synchronized spatiotemporally.

It is interesting to observe that if two groups of pedestrians arrive from opposite directions at nearly the same time, an interleaved passage pattern results, where the groups alternate in passing several pedestrians at a time. However, if one of the groups arrives significantly earlier than the other, the later group will wait until the earlier one finishes passing through the doorway (Fig. 12 bottom), which we also observed in our recorded real-world video.

(a) (b) (c)

Fig. 13. With similar initial starting positions (a) whether a particular pedestrian (yellow circled) is hurried (b) or not (c) will result in a different passing order.



(a) (b)

Fig. 14. Revolving door scenario simulations.

(a) (b)

Fig. 15. Double door scenario simulations.

Our simulated humans perform reasonable behaviors based on the current state of their world. If the follower is too far from the holder, the door will not be held. If the follower is a lady, the holder is more likely to hold the door and even to let the follower pass first. However, a hurried pedestrian will exhibit behaviors through the doorway that are consistent to a hurried state of mind, walking quickly, and becoming less apt to hold the door open for a follower to pass first. When a group of pedestrians approaches the door, the result will usually be that the hurried ones will pass through the doorway earlier than unhurried ones (Fig. 13), as expected.

6.2 Revolving Door Scenario Simulations

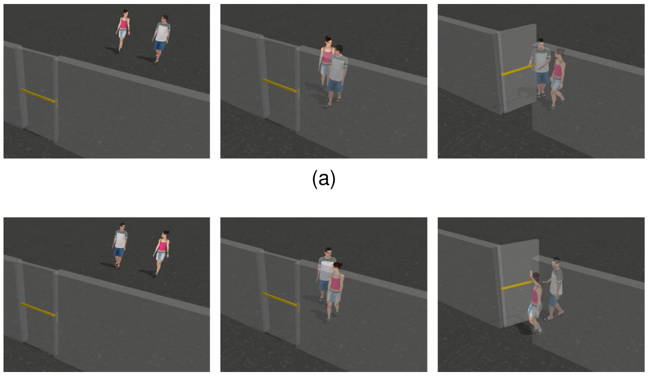
For a revolving door, pedestrians approaching from the same side can form a continuous flow (Fig. 14a). With pedestrians approaching from opposite sides, the simultaneous flow of both sides is ensured (Fig. 14b). Furthermore, based on when they arrive at the door, pedestrians can dynamically choose to speed up to catch the opening door or slow down and wait for the next opening.

6.3 Double Door Scenario Simulations

In the double door example, both features of preferring the right-hand door and the dynamic preference of the holder's side can be observed. In cultures that prefer passing on the right-hand side, pedestrians will usually choose the right-hand door and a two-way flow will result (Fig. 15a). If one door is in relatively heavy use while the other is clear, then the later arrivers will start using the less congested door, even if it is not the right-hand one. Moreover, if there is only one holder of one door with the other door clear, the next follower will select the holders side regardless of whether it is the left or right side (Fig. 15b).

(a) (b) (c)

Fig. 16. Perambulator scenario simulations.



(a)

(b)

Fig. 17. Simulation of friends walking together, shoulder to shoulder, which casually results in different passing orders ((a) versus (b)).

6.4 Additional Simulations

In scenarios of a pedestrian carrying a box (Fig. 2e) or pushing a perambulator (Fig. 16), the follower will try to overtake in order to open the door first and offer door-holding assistance to the carrier/pusher. In scenarios of two pedestrian friends walking shoulder to shoulder, they do not exhibit leader/follower dominance while approaching the door, until they arrive at the proper region for interacting with the door, resulting in an improvisational passing order (Fig. 17).

7 Conclusions and Future Work

We have introduced a simulation framework for synthesizing convincing multi-human animation subject to the rules governing socially acceptable behavior—i.e., etiquette—in and around a variety of doors. Our simulator synthesizes cooperative door-holding behaviors that have not previously been the subject of study in autonomous virtual humans. Our general framework can support the simulation of scenarios involving multiple autonomous pedestrians encountering different types of doors, including sprung single hinged doors, revolving doors, and sprung double hinged doors. Our efficient model generates continuous, dynamic, and diverse human simulation results, making it practical to realistically animate nontrivial multi-door/doorway, multi-character scenarios automatically and in real time.

Our system was designed to simulate relatively uncrowded scenarios, say 5 to 6 pedestrians waiting simultaneously at each side of a sprung single hinged door, and similarly for the revolving door and sprung double hinged door cases. These conditions elicit social behaviors that exhibit more respect to others, and a variety of cooperative actions. We have tested our simulator with two extreme cases of 12 same-side and 14 opposing-side pedestrians attempting to pass simultaneously (see [7] for the details and associated simulation results). Although our approach seems to be reasonably scalable, these denser scenarios occasionally lead to deadlocks in the doorway steering phase when there is no available locomotion command that can avoid collision in the local zone in which the pedestrian dynamically ends up. Indeed, in similar real-life scenarios people may sometimes have to yield way to those coming through the doorway in front of them, perhaps by stepping to the side or even backward. This would require a more capable locomotion and steering system than the one we have currently implemented. As the density of the crowd increases, people would need to consider other factors in improving the efficiency of the flow. This extension would be interesting future work.

For the purposes of the present work, we have assumed that doors are transparent, and pedestrians have full perception of the opposite side of the door. In the presence of opaque doors, a different doorway ordering protocol would be needed. During the doorway ordering phase, a pedestrian's perception would need to be constrained by partial visibility through the doorway, while the subsequent doorway ordering algorithms can remain intact.

In doorway ordering, we do not enable a committed follower to change their mind about passing next as doing so could give rise to more intricate scenarios where another pedestrian takes over and passes next. This merits future work. On the decision level, it will be preferable to acquire real-world data with which to train our Bayesian network model, or to train it on intensive data collected from user evaluations of simulation results. Quantitative studies of real-world videos can potentially validate current simulation results or quantify additional behaviors that can be incorporated into our model.

We demonstrated simulation results for a pair of friends passing though doors together. An interesting generalization would be to include additional social connections between pedestrians, such as pedestrians forming small groups whose cooperative behaviors transcend egocentric considerations. In such scenarios, one polite member of the group may choose to precede the others and hold the door open for them. Meanwhile, other pedestrians would recognize them as a group and refrain from interfering with their collective progress. Furthermore, gestures could be incorporated to non-verbally signal and reinforce these and other behaviors or to convey the laboriousness of certain door-holding actions [37].

Appendix A
Door Control Functions

Door opening is naturally affected by humans applying force at a relatively constant point on the door. We have created a procedural door controller which is not physically-based, but which provides flexible and stable human interaction. We build two functions for human interaction. The first function is the door rotation angle, determined by the relative position p_{rel} and absolute position p_{abs} of the hand on the door. It is employed in the door-holding phase when the holder needs to move their body while holding the door, so it is better to let the hand position determine the angle of the door: $f_a(p_{\mathrm{abs}}, p_{\mathrm{rel}})$. The second function is to obtain the absolute position of the hand given the door rotation angle a_{curr} and the relative position p_{rel} of the hand on the door: $f_{p_{\mathrm{abs}}}(a_{\mathrm{curr}}, p_{\mathrm{rel}})$. It is employed in the opening phase, when the door must be opened gradually to a certain angle, while the hand is fixed at a relatively constant position on the door.

The door has automatic opening and closing motion procedures that can be triggered, and it has a bouncing effect, which occurs when the person releases the door—he/she will apply extra force in order to conserve momentum, which results in the door opening to a larger angle and then closing back. We create a function to mimic this effect: $f_{\mathrm{bounce}}(a_{\mathrm{bounce}}, p_{\mathrm{stop}})$, where a_{bounce} is the extra angle the door will open, and p_{stop}, when provided, the door will stop closing if any part of the door board hits this position, and it is useful for the holder to hold the door after it bounces back.

Appendix B
States of the Door Interaction Model

This appendix details the primary states and associated key poses of the state-based door interaction model.

B.1 Reaching and Opening Door Phases (Prepare H)

When the holder is close enough to the BOP (Fig. 4 of the manuscript), the pedestrian will enter the *OpenerInit* state, and switch from doorway locomotion mode to using the procedural motion model. The next goal is to move to the BOP and assume a convenient full-body pose for opening the door. It is not trivial to determine the BOP. Based on our observations of real-world videos, humans tend to stop at the gap of the door facing at an angle that facilitates their handling-side arm to reach the door handle or push bar. We have manually defined the BOP and target body orientation, together with the target setting for the end-effector of the handling-side arm, such that the hand is at the door handle or push bar. This information is stored as a key pose and our procedural human motion model (described in Appendix C) will synthesize motion between the current pose and target pose (*ReachDoor* state). After completing the motion, the pedestrian will be in good start pose to open the door.

B.2 Pull versus Push

There are typically two door opening situations: the first is pulling the door handle from the outside, the second is pushing the door bar from the inside. In the pulling case, the holder must stand outside the circle formed by the opening door, so that the door will not collide with the holder's body when opened. In the pushing case, the holder must stand within the circle, so that when pushing and moving from inside, the holder will pass through the doorway rather than colliding with the walls on either side (refer to the BOP in both cases in Fig. 4 of the manuscript). To simplify the problem, we define the handling hand sides as the right hand for pulling the door and the left hand for pushing the door. There are multiple possible handling strategies, but we focus on the typical one to demonstrate the related behaviors.

The open door phase (*OpenDoor* state) is provided with a partially defined target pose that includes, in the pulling case, the spine rotation angle, with the constraint of the hand holding the handle, while in the pushing case, we have additional goals for the root, since the holder must move forward in order to push the door open. Given the goal pose, the procedural motion model will generate motions between the reaching and opening door poses. The door opens automatically and the handling side hand follows the handle or bar by acquiring its location from the door controller. After the holder achieves the goal pose, it will transition to the door-holding phase (*HolderDec* state).

If the previous holder did not hold the door, then as the next holder reaches the door, the door might not have fully closed. In that case, the next holder can interrupt the door closing procedure and continue to open it, which is more realistic.

B.3 Door-Holding Phase

Thus far, the holder does the sole work of handling the door. Meanwhile, if the current follower is ready (i.e., has reached the waiting region (Fig. 4 of the manuscript)), this follower will be committed, transition to procedural motion mode, and move to a position closely behind the holder from which it is convenient to take over the door. At this stage, the holder needs to commit to its decision to engage in door-holding behavior (*HolderDec* state). This is the critical motion phase mentioned in the manuscript and used in doorway ordering so as to prevent further changes in the follower role. The holding behaviors are summarized in Fig. 6 of the manuscript. Specifically, the holder has 3 different holding behaviors:

(1) Hold the door for others to pass later. The holder will maintain the holding pose until the follower has reached the door and holds it. After the holder releases the door, the follower will take over control of the door.
(2) Hold the door for others to pass first. The holder will maintain the holding pose while standing aside so that another pedestrian can pass through the doorway. After the follower passes through, the holder will either continue to hold the door for the next follower or release the door.
(3) Not hold the door for others. The holder will not wait until the follower reaches the door, but will release the door after opening it to the minimal angle that permits passage.

After the holder achieves the holding pose (*HoldDoor* state), the state transition is under the follower's control (*FollowerInit* state). Having completed the transition to the procedural motion mode, the follower needs to respond to the holder's behaviors with corresponding follower behaviors (*FollowerDec* state):

(1) Pass later (PL) is the response to the holder's behavior of holding the door for others to pass later. After the follower reaches the door (*ReachEdge* state), the state will transition to *ReleaseDoor* and the holder will release the door. Then, the follower will become the holder by transitioning back to *HolderDec* of *Critical Motion Phase* (red routine in Fig. 7 of the manuscript).
(2) Pass first (PF) is the response to the holder's behavior of holding the door for others to pass first. After completing the motion, the follower will transition to the normal locomotion/steering mode, and the state will transition back to *HolderDec* of *Critical Motion Phase* (blue routine in Fig. 7 of the manuscript). Then, the holder will make another door-holding decision for the next follower.

B.4 Releasing and Taking Over Door Phase

In the door releasing phase (*ReleaseDoor* state), if there is a PL follower, the transition works as mentioned earlier; if there is no follower or the follower decides to not hold the door, the next state will be *FinishDoor*, which will trigger the door closing motion. If the follower detects this state, it will become the holder, transition to *OpenerInit*, and restart the door opening procedure. In both cases, the holder will record the current procedural motion pose and prepare to blend to data-driven locomotion control. Our design has the advantage of reusing states and it will not be affected by the number of followers in the procedure.

Appendix C
Procedural Human Motion Generation

Research on animating manipulation tasks addresses motions that involve interactions with objects. Unfortunately, optimal motion planning subject to constraints [38], [39], [40] is computationally expensive for real-time multi-character applications. However, the motion of the lower-body around a door is highly constrained, and we have found that parameterizing the motions in step space [41], [42], [43], [44] offers an efficient approach to tackling this problem. We considered extensions to synthesize full-body motions under constraints [45], [46], but this was insufficient for dynamic situations involving interference from multiple pedestrians; hence, we devised our own motion synthesis solution that can achieve the required behaviors.

Our flexible procedural motion model synthesizes motions between two key poses that are specified by two states. Reviewing the door interaction procedure, the related key poses and possible transitions between them are shown in Fig. 18. During the door-holding procedure, given that the follower might become the holder, the next key pose will be decided as shown in Fig. 19. Given two key poses, a procedural motion model will generate motions between them, which enables continuous motion transitions under the environmental constraints.

Pedestrians must pause in certain poses, such as when holding the door. For the sake of realism, they must not become static—it is necessary to keep them subtly moving. To this end, we employ Perlin Noise [47].

C.1 Pose-to-Pose Procedural Animation

A full-body pose is comprised by the joint angles of some critical joints. A basic joint pose is a transformation

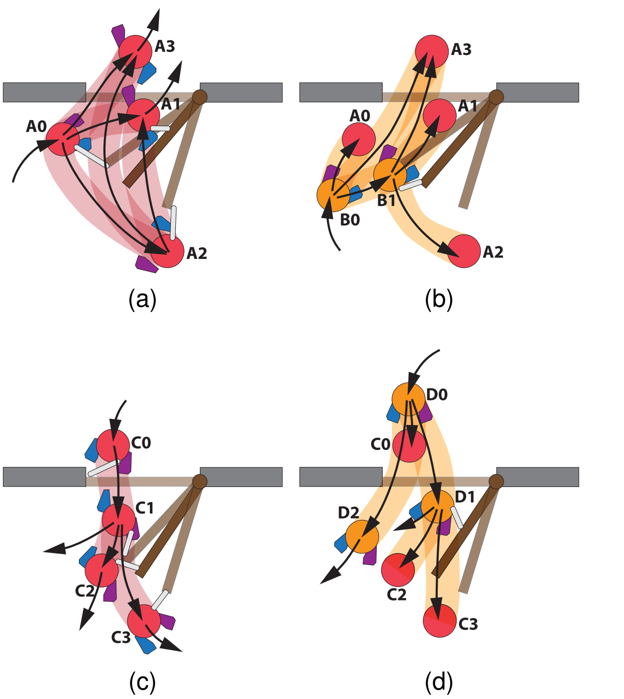


Fig. 18. The key poses (overhead view) and possible transitions between key poses occurring during door state transitions for the door pulling case (top) and door pushing case (bottom). The red circles denote holder poses and the yellow circles denote follower poses. The white bar represents the arm pose, the purple and blue bars represent the left and right feet pose respectively. The transitions are further explained in Fig. 19, which illustrates how the key poses and transitions associate with different door-holding behaviors.

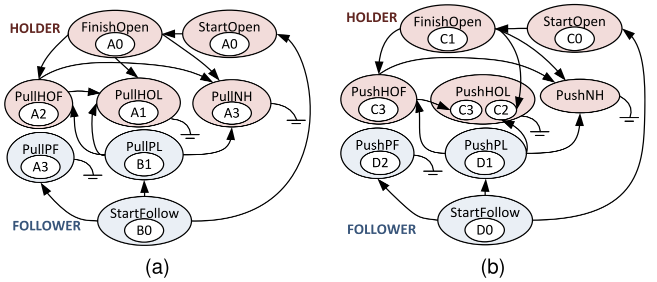


Fig. 19. The relationships between key poses and different holding behaviors. The red ovals represent holder behaviors, while the blue ovals represent follower behaviors. The contained white ovals denote key poses as indicated in Fig. 18. The character can transition its behavior from follower to holder.

configuration of a joint: $P = (p, \{r_q, (\theta_x, \theta_y, \theta_z)\})$, where P is a pose, p is position, and the rotational component can be represented either by a quaternion r_q or by rotation angles $\theta_x, \theta_y, \theta_z$, around the **x**, **y**, and **z** axes of the world coordinate system. A full-body pose is composed of some joint poses: $P_f = (P_{\mathrm{rt}}, P_{\mathrm{lh}}, P_{\mathrm{rh}}, P_{\mathrm{sp}})$, where P_{rt}, P_{lh}, P_{rh}, P_{sp} are the joint poses for the root, left hand, right hand, and spine. Given a current pose and a target pose, the procedural animation system will generate motions $G(P_f^c, P_f^t)$, where P_f^c and P_f^t are the current and target full-body poses. The root transformation will trigger the step-based procedural locomotion (described in the next appendix). Animating the spine requires gradually rotating the root joint until the target rotation is achieved.

The arm motion animation takes into account several constraints and is controlled by IK. For fast performance, we have adopted an analytical IK model [48] comprising 7-DOFs for the human linkage. Given a target pose, the arm end-effector will move gradually toward the target along the shortest path, until the arm reaches the target or the length limit. Since the body is possibly being moved by the root transformation, the current IK target configuration must be updated according to the updated setting of the shoulder frame, which is the coordinate system upon which the IK is based. This will ensure that the arm always moves toward the target without incorrect backward movement due to dramatic root transformation. Taking the right hand as an example, the current absolute position of the end effector is $p^c_{\mathrm{rh}} = r^c_{\mathrm{rs}} p'^l_{\mathrm{rh}} + p^c_{\mathrm{rs}}$, where p^c_{rh} is the current world position of hand, r^c_{rs} is the current world rotation of right shoulder joint, and p'^l_{rh} is the last frame's relative position of the hand w.r.t. the shoulder frame. p^c_{rs} is the current world position of the shoulder. Then the hand's next world target position can be calculated as $p^n_{\mathrm{rh}} = p^c_{\mathrm{rh}} + \Delta d$, where $\Delta d = ||p^t_{\mathrm{rh}} - p^c_{\mathrm{rh}}|| s \Delta t$, with p^t_{rh} as hand's target position, s as the hand speed, and Δt as the time step. If the target position p^n_{rh} is not reachable, we use p^c_{rh} as the target position. This method is used for animating reaching. In some other situations, the hand must follow the track of an object, such as when the holder pulls or pushes the door open. We add another hand control that can dynamically update the target pose of the hand between frames.

C.2 Step-Based Procedural Locomotion

Between two key poses, the character might undergo positional displacements of the root. Due to the highly constrained environment and the complexity of handling the door task, target root positions are defined for the characters to reach in each phase. An automatic step generation procedure will generate reasonable steps connecting the current to the target root position. The step-based procedural locomotion can generate full-body locomotion: $L(P^c_{\mathrm{rt}}, P^t_{\mathrm{rt}}, f, cs)$. The current foot configuration is $f = (P_{\mathrm{lf}}, P_{\mathrm{rf}}, sw, sd)$, where P_{lf} and P_{rf} are the current joint poses for the left and right foot, sw is the current swing foot side, sd indicates whether the current pose is standing or in the middle of walking; if standing, the first step will be generated as a special case. The constraints on the target step are denoted as $cs = (sd, bk)$, where sd indicates whether the last step is to a standing pose or just a pause in the middle of walking, and bk indicates whether the steps are generated as backward steps, which, when set to true, the step generation procedure works basically the same way, but the root orientation keys will be reversed when synthesizing full-body locomotion.

The step generation works as follows (Fig. 20a) in the case of current step is in the middle of walking ($sd = \mathrm{false}$): The methods mainly decides the position of the feet. The foot orientation is decided by the orientation of the root after steps are generated. We calculate the target root direction $\mathbf{d}_{\mathrm{tgt}} = ||\mathbf{p}^{\mathrm{tgt}}_{\mathrm{rt}} - \mathbf{p}^{\mathrm{curr}}_{\mathrm{rt}}||$, where $\mathbf{p}^{\mathrm{curr}}_{\mathrm{rt}}$ is the current root position and $\mathbf{p}^{\mathrm{tgt}}_{\mathrm{rt}}$ is the target root position. The right side direction is $\mathbf{d}_r = \mathrm{rot}(-\pi/2, \mathbf{y})\mathbf{d}_{\mathrm{tgt}}$, and the left side direction

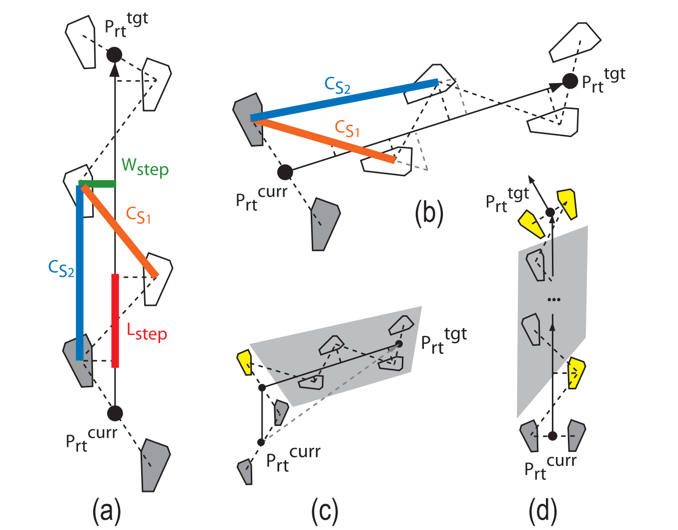


Fig. 20. Step generation. The gray footprints indicate the initial foot positions and the white and yellow footprints are the generated steps (a) A step sequence is generated between $p_{\mathrm{rt}}^{\mathrm{curr}}$ and $p_{\mathrm{rt}}^{\mathrm{tgt}}$. L_{step} and W_{step} are values for generating steps, and C_{S_1} and C_{S_2} are constraints for distance between the left and right foot positions and the distance one foot can step, respectively. (b) When a large turn is required, constraints C_{S_1} and C_{S_2} will efficiently constrain the foot positions to valid configurations. (c) An auxiliary step is generated if the target direction is behind the current support foot. (d) From a standing pose, the first step will be generated to close the distance; the target step will be regenerated with the target facing direction, if it is required to be a standing pose.

is $\mathbf{d}_l = -\mathbf{d}_r$. The next (right) step position is calculated and then constrained by C_{s_1} for different side-step distances

$$\mathbf{p}_{\mathrm{rf}_1} = \mathbf{p}_{\mathrm{rt}}^{\mathrm{curr}} + \alpha \mathbf{d}_{\mathrm{tgt}} L_{\mathrm{step}} + \mathbf{d}_r W_{\mathrm{step}}, \tag{1}$$

$$\mathbf{p}_{\mathrm{rf}_1} = \mathbf{p}_{\mathrm{lf}_0} + ||\mathbf{p}_{\mathrm{rf}_1} - \mathbf{p}_{\mathrm{lf}_0}|| C_{s_1}, \tag{2}$$

where the parameter α is set to 1.5. We can map the first step in the target root direction, and then calculate the second (left) step constrained by C_{s_2} for same side step distance

$$m_{\mathrm{rf}_1} = (\mathbf{p}_{\mathrm{rf}_1} - \mathbf{p}_{\mathrm{rt}}^{\mathrm{curr}}) \cdot \mathbf{d}_{\mathrm{tgt}}, \tag{3}$$

$$\mathbf{p}_{\mathrm{lf}_1} = \mathbf{p}_{\mathrm{rt}}^{\mathrm{curr}} + \mathbf{d}_{\mathrm{tgt}}(L_{\mathrm{step}} + m_{\mathrm{rf}_1}) + \mathbf{d}_l W_{\mathrm{step}}, \tag{4}$$

$$\mathbf{p}_{\mathrm{lf}_1} = \mathbf{p}_{\mathrm{lf}_0} + ||\mathbf{p}_{\mathrm{lf}_1} - \mathbf{p}_{\mathrm{lf}_0}|| C_{s_2}. \tag{5}$$

Similarly, we map the second foot in the target root direction as m_{lf_1}. The next step will be calculated as

$$\mathbf{p}_{f_{\mathrm{next}}} = \mathbf{p}_{\mathrm{rt}}^{\mathrm{curr}} + \mathbf{d}_{\mathrm{tgt}}(L_{\mathrm{step}} + m_{f_{\mathrm{prev}}}) + \mathbf{d}_s W_{\mathrm{step}}, \tag{6}$$

where $\mathbf{d}_s$ is chosen between $\mathbf{d}_r$ and $\mathbf{d}_l$. If $L_{\mathrm{step}} + m_{\mathrm{last}} > L_{\mathrm{tgt}}$, where $L_{\mathrm{tgt}} = ||\mathbf{p}_{\mathrm{rt}}^{\mathrm{tgt}} - \mathbf{p}_{\mathrm{rt}}^{\mathrm{curr}}||$, we generate the last step as

$$\mathbf{d}_1 = ||\mathbf{p}_{\mathrm{rt}}^{\mathrm{tgt}} - \mathbf{p}_{f_{\mathrm{last}}}||, \tag{7}$$

$$l_1 = W_{\mathrm{step}} / \sin(\mathrm{ang}(\mathbf{d}_1, \mathbf{d}_{\mathrm{tgt}})), \tag{8}$$

$$\mathbf{p}_{f_{\mathrm{end}}} = \mathbf{p}_{\mathrm{rt}}^{\mathrm{tgt}} + \mathbf{d}_1 l_1. \tag{9}$$

We must add an extra turning support step if the line between $p_{\mathrm{rt}}^{\mathrm{curr}}$ and $p_{\mathrm{rt}}^{\mathrm{tgt}}$ goes behind the current supporting foot (Fig. 20c). If the current step is standing, the first step is generated closer to the initial foot position (Fig. 20d) by setting α to 1.0 in (1). If the last step is required to be standing, and given the normalized right direction of the target facing direction as $\mathbf{d}'_r$, the last two foot positions are regenerated (Fig. 20d)

$$\mathbf{p}_{\mathrm{lf}_{\mathrm{end}}} = \mathbf{p}_{\mathrm{rt}}^{\mathrm{tgt}} - \mathbf{d}'_r W_{\mathrm{step}}, \tag{10}$$

$$\mathbf{p}_{\mathrm{rf}_{\mathrm{end}}} = \mathbf{p}_{\mathrm{rt}}^{\mathrm{tgt}} + \mathbf{d}'_r W_{\mathrm{step}}. \tag{11}$$

Based on the generated steps, procedural full-body locomotion will be synthesized. We create a walking motion profile with feet, root, and hand keys. The root will have keys in the two-foot support phase, and its orientation will decide the orientation of the adjacent foot keys. Both hands have keys in the two-foot support phase, and have the front extreme key when the same side foot is at the back, and back extreme key when the same side foot is at the front. Finally, the root has keys in the middle of the single foot support phase, when the root reaches the highest height in the walking cycle, and it has keys in the two-foot support phase when the root reaches the lowest height. While animating the motion, the feet, root, and hands are synchronized for coordinated full-body locomotion.

TABLE 4
Details of the Side-by-Side Comparison Videos Used in the Survey

	agent count	video length (secs)	manipulated variable
Comparison 1	2	11	Rush
Comparison 2	2	10	Care
Comparison 3	5	12	Rush
Comparison 4	5	20	Rush and Kindness

Appendix D
Evaluation of the Social Factor Settings

To validate the realism of our simulated results, we developed and conducted a survey using Amazon Mechanical Turk that included 16 male and 12 female anonymous participants with US bachelor or higher degrees. Each participant watched 4 side-by-side simulation videos and in each case was asked to choose the video that exhibited more of a certain trait.

Table 4 presents the details of the comparison videos used in the survey. In Comparison 1, the "Rush" factor was set to 0.2 versus 0.8, such that in one video the holder holds the door for the follower, but not in the other video. We choose these values because they are intermediate between the extreme values (0.0 and 1.0) and the neutral value (0.5). In Comparison 2, the "Care" factor was set to 1.0 versus 0.0, such that in one video the holder holds the door for a female follower to pass first, whereas in the other video the holder holds the door for a male follower to pass later. In Comparison 3, the "Rush" factor was set to 0.8 versus 0.2, such that in one video one person (wearing a red shirt) in a group speeds up and passes through the door sooner than in the other video. In Comparison 4, the "Rush" factor was set lower and the "Kindness" factor was set higher for one video relative to the other, such that in one video a group of

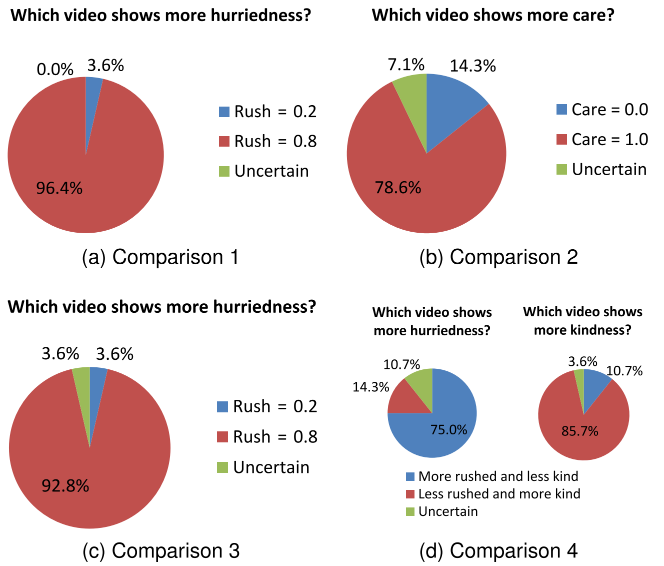


Fig. 21. User response distributions for the simulated video pairs.

people hold the door more frequently for followers than they do in the other video.

The questions asked after observing each side-by-side pair of videos are:

(1) Comparison 1: In which video is the pedestrian that opens the door in a greater hurry?
(2) Comparison 2: In which video is the pedestrian that opens the door showing greater care toward the follower?
(3) Comparison 3: In which video is the pedestrian wearing the red shirt (also circled in yellow at the beginning) in a greater hurry?
(4) Comparison 4 (1): In which video are pedestrians in a greater hurry?
(5) Comparison 4 (2): In which video do pedestrians show greater kindness?

The choices for each question include “left side video”, “right side video” and “hard to tell”. Comparison 4 involves two questions because two factors were modified.

As shown in Fig. 21, the participants predominantly chose the video of the simulation with a larger value of the parameter affecting the trait in question. In particular, they consistently identified hurriedness, given that the character of interest in one video speeds up and passes through the door earlier than it does in the other video (Figs. 21a and 21c). While participants generally identified that holding the door open for others to pass first demonstrates greater care than holding the door open for others to pass later, this identification was slightly less consistent than the identification of hurriedness (Fig. 21b). When observing a group of people with certain traits, the traits were less obvious to identify and resulted in larger response variance although the dominant choice remains correct (Fig. 21d).

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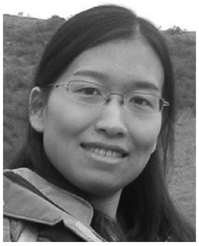

Wenjia Huang received the PhD degree in computer science from the University of California, Los Angeles, in 2014. Her research interests include behavioral animation, pedestrian simulation, and virtual human simulation. Currently, she is a software engineer in the visual technology team at Houzz, Inc. Previously, she was a software engineer in the game service team at Amazon.com, Inc. She is a member of the IEEE.

Demetri Terzopoulos received the graduate degree in honours electrical engineering from McGill University and the PhD degree in artificial intelligence from the Massachusetts Institute of Technology (MIT), in 1984. He is a chancellor's professor of computer science with the University of California, Los Angeles, where he holds the rank of distinguished professor and directs the UCLA Computer Graphics & Vision Laboratory. He is also co-founder and chief scientist of VoxelCloud, Inc. He is or was a Guggenheim fellow, a fellow of the ACM, IEEE, Royal Society of Canada, and Royal Society of London, and a member of the European Academy of Sciences, the New York Academy of Sciences, and Sigma Xi. Among his many awards are an Academy Award for Technical Achievement from the Academy of Motion Picture Arts and Sciences for his pioneering work on physics-based computer animation, and the inaugural Computer Vision Distinguished Researcher Award from the IEEE for his pioneering and sustained research on deformable models and their applications. ISI and other indexes list him among the most highly-cited authors in engineering and computer science, with more than 300 published research papers and several volumes, primarily in computer graphics, computer vision, medical imaging, computer-aided design, and artificial intelligence/life. He has given approximately 500 invited talks around the world about his research, including more than 100 distinguished lectures and keynote/plenary addresses. He joined UCLA in 2005 from New York University, where he held the Lucy and Henry Moses Endowed Professorship in Science and was professor of computer science and mathematics at NYU's Courant Institute of Mathematical Sciences. Previously, he was professor of computer science and professor of electrical and computer engineering at the University of Toronto. Before becoming an academic in 1989, he was a program leader at Schlumberger corporate research centers in California and Texas. He is a fellow of the IEEE.