Computers & Graphics 34 (2010) 677–687

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Graphics for Serious Games

A head movement propensity model for animating gaze shifts and blinks of virtual characters

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ARTICLE INFO

Keywords:
Gaze shifts
Blinking
Virtual characters
Serious games

ABSTRACT

An automatic model is presented for animating gaze shifts of virtual characters towards target locations in a virtual environment. Two connected components are described: an eye–head controller and a blinking controller. The gaze control model is based on results from neuroscience, and dictates the contributions of the eyes and head to a gaze shift according to an individual's head movement propensity; that is, their tendency to recruit their head when making gaze motions under different conditions. The blink controller simulates gaze-evoked blinking, a specific category of behaviours that accompany gaze shifts. The probability of occurrence of such blinks, and their amplitude, is related to the gaze shift. The model forms the basis for a number of experiments investigating the impact of blinking, eye–head ratio and direction of head movements on user perception. In addition to other application domains, the findings are of significance to serious games environments, where the perceived quality of a character's gaze may affect engagement, immersion and learning outcomes.

1. Introduction

Virtual characters form an integral part of applications featuring virtual environments, from computer entertainment titles to serious games. The purpose of such characters may merely be to contribute to the overall believability of scenes, by being visible as crowds of spectators in the background, or may be more active and prominent, by engaging in close-up interaction with the user, for example during pedagogical situations, as is the case with Embodied Conversational Agents (see, for example, Greta [7]).

Given the wide repertoire of behaviours that a virtual character must be capable of engaging in, one of the most fundamental is the ability to attend to the user and environment in an appropriate manner by orienting the head and eyes to fix the line of sight. As noted in [13], many animals, including horses and rabbits, have eyes in the lateral areas of their heads, removing the need to substantially reorient them when changing the line of sight. In contrast, human eyes are set into the front of the skull: given the anatomy of the eye, where highest acuity is constrained to a small area near the centre, gaze shifts are a common component in the reorienting of one's attention. Additionally, eye-gaze can be employed as a signaller of interpersonal attitudes and emotions. Its close relationship to the perception and visual attention mechanisms of the organism helps adversaries and allies to infer internal state, seek motives for past behaviour, or theorise about imminent future action (Fig. 1). Gaze shifts are a common and expected behaviour for humans, and therefore also one expected to be seen from humanoid characters inhabiting virtual environments.

Unfortunately, animating gaze to a high quality in an automatic manner remains a difficult prospect. While alternatives exist based on recording the animation of characters' bodies, for example using motion capture techniques [22], or for capturing eye movements alone [21], capturing gaze during free-viewing situations remains challenging. Other approaches, where models are constructed from experimental data, are also troublesome: while comprehensive experimental results and models exist for gaze movements taking place in the horizontal meridian [10] for example, far more remains to be uncovered regarding the nature and circumstances surrounding vertical and oblique gaze shifts [9]. Thus, motions are usually either animated by hand, or else employ simplified models where the perceptual impact of gaze parameter variations is unclear.

Here, some challenging low-level aspects related to gaze shifts are explored for application to virtual characters: (1) the variability in motion between participants when they shift gaze to targets at similar eccentricities, (2) the relationship between blinking and gaze shifts, and (3) the relative contributions of the eyes and the head under varying circumstances. These are accomplished using an eye–head controller (Section 3) that automatically generates gaze shifts for a character based on the

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doi:10.1016/j.cag.2010.09.007

Fig. 1. Gaze is a salient behaviour in the environment, providing an abundant source of information for others about entities' possible intentions and imminent future actions [2]. Animating the gaze of virtual characters, such as this Embodied Conversational Agent called *Greta* developed by Pelachaud and colleagues [7,33], is an important factor in creating credible environments and interactions that facilitate user engagement and immersion.

concept of *head movement propensity*; that is, the idiosyncratic tendency for individuals to employ differing head and eye contributions to their gaze motions [28]. Characters are assigned a *head movement factor* that designates them along a continuum between two categories of *extreme head-movers* and *extreme non-movers*. A blink controller (Section 4) links blinking motions to shifts in gaze, referred to as *gaze-evoked blinking*, to account for alteration in blink rate and the amplitude of eyelid closure.

The model presented here employs these capabilities in order to probe viewers' perception of gaze. This issue is significant for animation: While the addition of more complicated rules for gaze control may make a model more realistic, it may be of little value if there are few noticeable improvements from the viewer's perspective. For this reason, experiments were conducted focusing on the following questions:

- Are some blinking strategies, accompanying gaze shifts, perceived as more natural than others?
- Are different eye–head ratio configurations perceived as more natural than others?
- Are there differences in the perception of horizontal and vertical gaze shifts made by virtual characters?

Results are presented in Section 5 and applications for the model, with a focus on those in Serious Games, are described in Section 6.

2. Previous work

The categorisation described by Poggi et al. [33] is useful for describing some of the types of gaze control models under development. Eye gaze may be perceived to have at least four different functions: seeing, looking, thinking and communicating. The eyes may be used for capturing information from the environment through visual perception, or orienting the direction of one's gaze with the goal of obtaining visual information about potential regions of interest. Our eyes may shift when we are thinking or experiencing other endogenous states, and may also be used intentionally to communicate with somebody.

A number of previous works have considered gaze (Section 2.1) and blink (Section 2.2) control under a variety of conditions, as described next.

2.1. Gaze control

Most, if not all systems employing animated characters, require some form of gaze control system. Despite this, systems are often proprietary and details are not published. A number of works have focused on gaze control and eye movements at varying levels, usually during conversational settings. Gaze generation for turn-taking and conversation [5,33], displaying attention and interest during interaction [31], during multiparty situations [14] and for full-body emotional expressivity [20,37] have also been studied.

Gaze control has also been studied at higher levels of direction, relating to visual attention models for detecting salient or task-relevant regions of virtual environments [6]. Peters and O' Sullivan [30] and Itti et al. [16] orient the head and eyes of an agent towards locations derived from a neurobiological model of attention. In particular, Itti and colleagues have provided some of the most comprehensive models published to date for low-level gaze and blinking [17].

Many challenges are also evident in relation to how gaze may be interpreted. Perceptual studies, in virtual and immersive environments, have considered gaze behaviour, for example, when compared with the graphical appearance of the character [12] and during dyadic interactions [38]. An assessment of eye-gaze [24] also highlights its quality for gaze following, and its impact on the perception that one may have of the other's attention towards them [27].

In this work, the primary concern is how the eyes contribute to the role of looking; that is, how the gaze animation takes place, as opposed to the determination of where it should be targeted. In this respect, elements of the work of Lance and Marsella [20] and Itti et al. [17] are perhaps of the most direct relevance to the current work.

2.2. Blinking

The synthesis of blinking behaviours has been primarily considered when applying eye movements to conversational agents, usually based on internal emotional or conversational state parameters. In the A.C.E. system, as is the case for real humans [15], an agent's anxiety level has an effect on the frequency of eye blinking [18]. Blinking is also considered in [17], depending on locations attended to and timing considerations, each blink lasting for a fixed amount of time.

A number of other studies have considered human impressions of blinking. These studies are of great importance to synthesis attempts, as they provide information on how different behaviours may be perceived. For example, [25] studied how variations in the frequency of blinking were interpreted in terms of impressions of nervousness, unfriendliness and carelessness, providing evidence of the important role of blinks in impression formation. In [36], the blink rate of an avatar was shown to have a significant impact on viewer impressions, an effect that was greater for human-style avatars than other types.

2.3. Scope of current work

This work focuses specifically on gaze shifts and the blinks that accompany them; that is, moderate- to large-scale shifts in eye and head configuration that often accompany a covert change in focus of attention from one location or object to another. Unlike previously proposed models, that presented here provides variation in gaze based on a *head movement factor* and models the role of specialised gaze-evoked blinks during gaze shifts. It represents only one capability in what may be considered a complete gaze model: other types of eye-gaze behaviour, such as smooth pursuit of moving objects and saccadic movements (e.g., predictive, visually- or memory-guided saccades, or reflexive vs. voluntary [34]) are not accounted for, nor are blinks associated with

Fig. 2. Top-down view (left) of the virtual character configuration and gaze determination vectors, and (right) the corresponding frontal view. $\vec{M}$ is the midline vector, $\vec{H}$ is the head vector and $\vec{E}$ is the eye vector. The objective of the gaze controller is to align the eye vector onto a target position with head contributions that may vary between different characters.

Table 1
Definitions describing gaze computations.

Attribute	Meaning
$\vec{M}$	Midline Vector
$\overrightarrow{HM}$	Extreme head-mover vector
$\overrightarrow{NM}$	Extreme non-mover vector
$\vec{H_c}$	Current head vector
$\vec{H_f}$	Final head vector
$\vec{E_c}$	Current eye vector
$\vec{E_f}$	Final eye vector
$\vec{T}$	Target vector from head position to target position
OMR	Oculomotor range, -40° and $+40^\circ$ horizontally
HMR	Head movement range
HMF	Head movement factor ranging from 0.0 to 1.0

psychological or exogenous factors. Nonetheless, it is expected that other eye-gaze and blink models, such as the statistical saccadic eye movement model presented by Lee et al. [21], would be both compatible with and complementary to the model presented here.

3. Eye and head movements

When looking around, targets may appear at different eccentricities within our environment with respect to our current gaze direction; if these eccentricities are outside of the mechanical rotational limits of our eyes, the *oculomotor range* or *OMR* (40°–55° eccentricity in humans), then the recruitment of the head in the final motion is mandatory for aligning the visual axis with the target. Such *gaze shifts* consist of coordinated eye and head movements in order to bring the foveal region onto the target and may also be common when looking at targets of eccentricities smaller than the OMR.

Gaze, G, is the direction of the eyes in space, which consists of the direction of the eyes within the head, E, and the direction of the head in space, H: see Fig. 2 for an illustration of these vectors and Table 1 for a list of definitions that will be used to describe gaze computations. Thus, Eq. (1) describes gaze direction in terms of the eyes and head, where *WS* is the world-space coordinate frame and *HS* is the head-space coordinate frame:

$$G_{WS} = H_{WS} + E_{HS} \tag{1}$$

Since the eyes and the head contribute to gaze motions, a primary issue when modelling gaze is the relative contributions of each to the final gaze motion. Although gaze shifts for humans and Rhesus monkeys are generally thought to follow a linear relationship linking head contribution and gaze amplitude (see [39]), the contribution of the eyes and head of an individual to the final motion can exhibit a reasonable degree of variability: for example, Afanador and Aitsebaomo [1] found that half of their participants consistently moved their heads, even when targets were well within the OMR and head movements were not mandatory. The other half produced head movements only for eccentricities beyond 20°–30°. Participants were categorised [3] into two distinct groups, *head-movers* and *non-movers*.

Fuller [11] further detailed a number of effects that may be used to explain these behaviours. As noted, horizontal human head movements are generally mandatory when the gaze shift demands an ocular orbital eccentricity exceeding the OMR. If a gaze saccade can be executed within this orbital threshold, then the amplitude of the head movement is regarded as being *discretionary* and the extent to which the head moves is referred to as *head movement propensity*, an individual's innate propensity towards moving their head. Here, two effects are highlighted, where *gain* is the relative contribution of the head to the total gaze motion: *Midline attraction* refers to a resistance to head movement away from the midline in non-movers and an increase in the head movement amplitude if a jump in gaze starts eccentrically. *Resetting* occurs when the eccentricity of a jump is varied, resulting in the stopping position being reset closer to the target.

Previous experiments (see [9] for an overview) have indicated a close, general relationship between the contribution of the head to the motion, referred to as *gain*, given the initial eye position and desired gaze shift. However, as noted previously, the gain may typically vary somewhat from individual to individual. Here, a gaze controller animates the gaze shifts of different characters according to head movement propensity as described next.

3.1. The gaze controller

At the lowest level, the task of the gaze controller is to animate the hierarchy of the virtual character so that the final configuration is such that the eyes are oriented towards a target location in the environment. The gaze controller presented here is simplified and only affects a subset of the character's hierarchy, corresponding to its head and eyes. The virtual character's eye position is represented by a single transformation, placed midway between the eye positions, approximating the viewpoint of the character. The orientation of this viewpoint is locked to the orientation of the eyes of the character.

Characters are attributed with a *head movement* factor, *HMF*, ranging from 0.0 to 1.0, signifying their propensity towards head movement or eye movement; that is, characters vary between being extreme *head-movers* and extreme *non-movers*. This attribute is used by the gaze controller to provide simplified midline attraction and resetting effects as described by Fuller. This essentially determines the gain, or head contribution, to gaze motions made by the virtual human; if the gain is high, then gaze shifts will consist primarily of head movements, while a low gain will involve primarily eye movements.

The gaze controller operates by creating a final head vector $\overrightarrow{H_f}$ and final eye vector $\overrightarrow{E_f}$. Initially, two head vectors are created with respect to the target. The first vector, $\overrightarrow{HM}$, represents the most extreme head movement vector; that is, gain will be maximum when the head is oriented with the target and the eyes do not make any contribution to the gaze unless the target is eccentric beyond that afforded by head movement limits alone. In such cases, the head movement is maximised and eye movement composes the remainder of the orientation (see Fig. 3). A second vector, $\overrightarrow{NM}$, is constructed to represent extreme non-movers. If the target is within *OMR*, and eye movement is thus discretionary, then extreme non-movers always use an eye movement to conduct the gaze [1]. If the target is outside of oculomotor range, then $\overrightarrow{NM}$ is aligned such that the eye vector is at its maximum; that is, the range of *OMR*. Note that any targets that are outside of *HMR* + *OMR* cannot be looked at by the current algorithm, since eye and head contributions alone are not enough to generate alignment with the target. Such cases could typically be resolved using an algorithm that also accounts for the character's upper torso when planning orienting motions.

For cases where the current head vector $\overrightarrow{H}$ is on the opposite side of $\overrightarrow{M}$ with respect to $\overrightarrow{T}$, resetting is simulated for non-movers by moving $\overrightarrow{NM}$ closer to $\overrightarrow{HM}$, and thus, closer to $\overrightarrow{T}$ (see Fig. 4). The final head vector $\overrightarrow{H_f}$ is then calculated as an interpolation of *HMF* between $\overrightarrow{NM}$ and $\overrightarrow{HM}$ (see Section 3.2). The eye vector $\overrightarrow{E_f}$ is the vector from the eye position to the target (with a value between 0 and the oculomotor range *OMR*). When the target vector $\overrightarrow{T}$ is within *OMR*, non-movers tend to use mainly their eyes to fixate the target. However, non-movers are more likely to maintain their head position close to the midline due to midline attraction. This means that in certain cases where the target vector $\overrightarrow{T}$ is between the current head vector $\overrightarrow{H_c}$ and the midline $\overrightarrow{M}$, the head is attracted back towards the midline (see Fig. 5).

The outputs of this process are two vectors, $\overrightarrow{HM}$ and $\overrightarrow{NM}$, representing the final eye and head directions for extreme head-movers and extreme non-movers, respectively. A high *HMF* value results in large head contributions to the final gaze animation, while a lower *HMF* involve a greater use of the eyes. Once the final vectors have been computed, the gaze animation accounts for the temporal details of the motion, as described next.

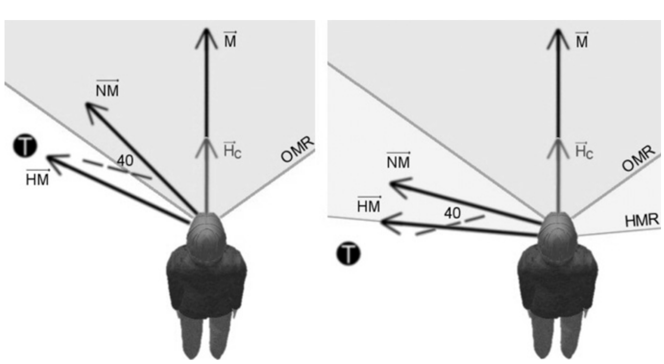

Fig. 3. Calculation of extreme movement vectors when targets are outside of *OMR* and outside of *HMR*. (Left) When a target is outside of *OMR*, head movements are mandatory, even for non-head movers. (Right) $\overrightarrow{HM}$ cannot extend beyond the maximum head rotation range *HMR*. Therefore, when the target is outside *HMR*, $\overrightarrow{HM}$ is set to *HMR* and eye movements are mandatory. In both cases, the extreme non-mover vector $\overrightarrow{NM}$ remains as close as possible to the midline vector $\overrightarrow{M}$.

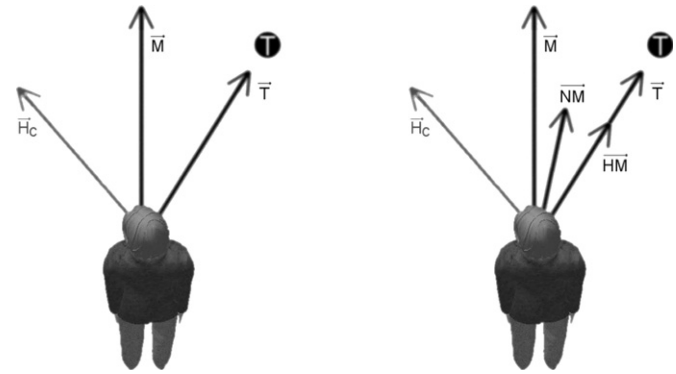

Fig. 4. The resetting effect. (Left) The target vector $\overrightarrow{T}$ is on the opposite side of the midline $\overrightarrow{M}$ to the current head vector $\overrightarrow{H_C}$. (Right) The extreme non-mover vector $\overrightarrow{NM}$ is brought closer to the target vector $\overrightarrow{T}$ in what can be thought of as the effects of momentum.

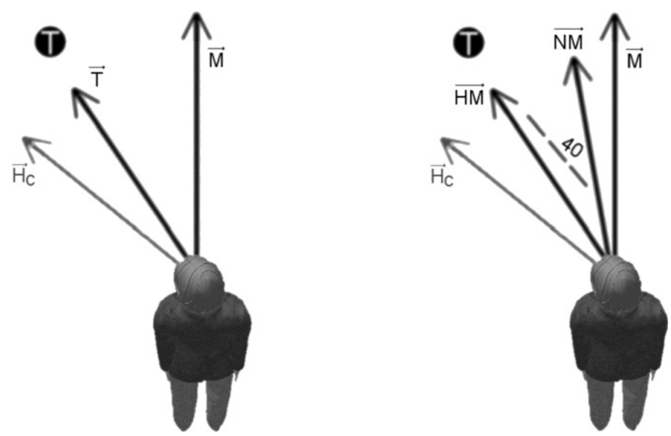

Fig. 5. Illustration of midline attraction. (Left) The target vector is between the midline and current head vectors. (Right) The extreme non-mover vector $\overrightarrow{NM}$ is attracted towards the midline such that the eyes are at the limits of *OMR*.

3.2. Dynamics

Given the output vectors, $\overrightarrow{HM}$ and $\overrightarrow{NM}$, representing the final eye and head directions for extreme head-movers and extreme non-movers, respectively, a *spherical linear interpolation*, or SLERP (see [35]), is used to provide the final eye and head orientations for the specified head movement factor (see Fig. 6).

It should be noted that the model presented thus far generates only the final head and eye orientations, but does not specify intermediate positioning, i.e. the relative timings and velocities of eye and head movements are not yet accounted for. At this point, a straightforward spherical linear interpolation operation may be conducted for each of the head and eyes, between their initial and final orientations. This method was adopted for the experiments in Section 5.

During actual gaze shifts, eye and head velocities exhibit peaks which are not always related in the same way: peak eye velocities may decline while peak head velocities increase with increasing gaze amplitude and gain (see [10]).

3.2.1. Velocity profiles, amplitude and duration

General relations are known to exist in the horizontal meridian between the duration, peak velocity and amplitude. In this model,

Fig. 6. Screenshots illustrating multiple frames from the gaze model in operation for varying gaze types and targets. Below each frame, eye and head directions and their ranges are depicted.

this data is generalised for vertical and oblique movements. Prototypical relationships are defined for the velocity profiles of the eye and head, according to those described in [9] and modelled using splines. Splines are altered at run-time for specific movements based on the maximum (or peak) velocity for the motion, and the amplitude of the motion i.e. the size of the head or eye movement, according to the extent of the recruitment of the eyes and head to the gaze shift.

3.2.2. Timing of head and eyes

The relative timing of the movements of the head and eyes is another factor of importance. This is accomplished by shifting the profile for the eyes along the temporal axis, so that the eye movement can happen slightly before, at the same time, or after the head movement. In all cases, it is ensured that the eyes reach the target either before or at the same time as the head. In the majority of cases, where the eyes fall on the target before the head, it is necessary to simulate the effects of the vestibulo-ocular reflex as described next.

3.2.3. Vestibulo-ocular reflex

The vestibulo-ocular reflex, or VOR, is important for keeping the eyes on-target when the head is rotating. Here, the VOR is necessary for situations when the eyes arrive at the target first. Technically, this is easily accomplished: once the eyes have been deemed to land on the target and while the head continues to rotate, new eye vectors are calculated based on the difference between the current head direction and the current target direction relative to the eyes. This process continues until the head has rotated onto the target.

4. Blinking

Blinking motions, often subtle, may offer an overlooked way of conveying a sense of realism in gaze motions. As with gaze motions, blinks may be interpreted in many different ways. Generalities have been described in the literature: individuals who do not blink or move their eyes may appear to be preoccupied or engaged, while high rates of blinking may indicate aroused internal states such as frustration, confusion or excitement. On average, a person blinks roughly 17,000 times per day, with a "normal" blink rate thought to be in the region of 20 blinks per minute [19]. Each blink lasts from 20–400 ms, with the primary purpose of clearing debris from the eye and moistening surface tissue.

The relationship between gaze and blinking is undoubtedly intricate and its complexity easily underestimated. Professional animators and artists have recognised the importance of blinking, and regard it as an important factor in creating expressive and life-like characters [23]. Despite this, little in-depth research into automated blinking models for autonomous characters appears to have taken place; most blink models, when published, appear to be of an *ad-hoc* nature, accounting solely for default blink rate related to emotional state or conversational role.

The factors affecting blink rate can be categorised as environmental factors and internal factors. Environmental factors include alterations in temperature, lighting and airflow that have an effect on blinking, as do factors affecting the ocular surface, such as wind. Different activities may also cause changes in blink rate, for example, engaging in conversation or concentrating on a visual task. Blink rate is also linked to internal psychological and physiological factors; for example, it may increase with excitement, frustration and anxiety or decrease with guilt and low mental load [15]. Age, gender, muscular tension and a variety of additional factors also appear to affect blink rate.

4.1. Gaze-evoked blinking

Gaze-evoked blinking motions are a specific category of blinks that accompany saccadic eye and head movements, in contrast to normal blinks that are elicited by external stimulation such as wind. Many vertebrates generate gaze-evoked blinks as a component of saccadic gaze shifts. As noted by Evinger et al. [8], such blinks appear to serve the purpose of protecting the eye during the movement, while also providing lubrication to the cornea at a time when vision has already been impaired due to the saccade. Evinger et al. describe three main characteristics of gaze-evoked blinks:

1. The probability of a blink increases with the size of the gaze shift. In the study conducted by Evinger et al., blinks were found to occur with 97% of saccadic gaze shifts larger than 33°, while the occurrence of eyelid activity for 17° eccentricity was only 67%.
2. The initiation of the activation of the eye muscle is dependent on the magnitude of the head or eye movement. Activation of the eye muscle started after the initiation of the head movement, but there was a clear tendency for activity to start before the head movement with large amplitude gaze shifts.
3. The amplitude of the head movement has been shown to affect the magnitude of the blink, or how much the eyelid closes (see Fig. 7). In general, the more the head moves, the more the eyelid tends to close. For example, during a head movement of 5° eccentricity, the blink magnitude will usually be quite small, meaning that the eyelids will not close very far. In contrast, eccentricities of 50° or more will often result in a full closure of the eyelid.

The general characteristics of gaze-evoked blinking detailed in [8] are implemented in the *blink controller*, as described next.

4.2. The blink controller

In addition to generating regular blinks, the blink controller also takes input from the gaze controller in order to generate gaze-evoked blinks. When a gaze request is made, the gaze

Fig. 7. Illustration of blinking magnitudes for the virtual human. Magnitudes from left to right are 0% (eyelid fully opened), 50% and 100% (eyelid fully closed). Gaze-evoked blinks may often have amplitudes below 100% and are proportional to the eccentricity of a gaze shift.

controller relays relevant information to the blink controller, such as the starting time of the gaze and the gaze amplitude. The blink controller then plans and schedules the blink motion.

The blink motion is planned as follows. First of all, head movement amplitude is used to determine if a blink is to occur. This is conducted probabilistically, where the probability of a gaze-evoked blink occurring is modelled as having a simple linear relationship with respect to the amplitude of the head movement, such that the probability of a blink for targets of 20° eccentricity is 20%, and the probability of a blink for targets of 50° or more eccentricity is 60%. In this way, a gaze-evoked blink will always take place for head movement amplitudes of 75° or more.

If a blink event is imminent then the blink magnitude is calculated, specifying by how much the eyelids should close. Blink magnitude is modelled as a linear relationship between the amplitude of the head movement, such that the magnitude of a blink for targets of 17° eccentricity is 67% and the magnitude of a blink for targets of 33° eccentricity is 97%.

5. Experiments

A number of perceptual experiments were conducted in an attempt to address the following questions:

1. Are some blinking strategies perceived as being more natural than others? A particular focus here was on whether people noticed blinking at all and the performance of those strategies featuring gaze-evoked blinks with normal regular blinking.
2. As described in Section 3, the degree to which the head may be recruited to a gaze motion may be idiosyncratic. Are some eye–head ratios perceived as being more natural than others?
3. Are there differences in the perception of horizontal and vertical gaze shifts? Most of the literature and experimentation concerns movements on the horizontal meridian only. This question probed potential differences in perception between motions taking place in the horizontal and vertical meridians.

Experiments addressing the first question above are described in Sections 5.1, 5.2, 5.3 and 5.4. Experiments for the remaining two questions are described in Sections 5.5 and 5.5.1. A discussion of these questions in light of the findings of the results is given in Section 5.6.

5.1. Blinking pilot study

A pilot study was conducted in order to assess the plausibility of gaze and blinking animations created by the system. Six participants (5M:1F) from computer science backgrounds, aged between 20 and 28, were shown multiple animations of a male virtual character making a series of eye and head movements.

Each trial was the same apart from the BlinkType, which had five conditions: no blink (NB); regular unsynchronised (RU); gaze-evoked (GE); probabilistic gaze-evoked (PGE); regular + probabilistic gaze-evoked (R+PGE)—see Table 2. In this study, the character appeared in the near (N) condition at all times: it was close to the screen and its eyes were clearly visible. Each animation lasted approximately 30 s. Participants were instructed that they would witness a virtual character making gaze motions, and were asked to rate the naturalness of the character's behaviour on a scale of 1–10 at the end of each trial. They could also provide a textual description of their impression of the behaviour.

5.2. Pilot study results

The averaged results obtained over all six participants are depicted in Fig. 8: Left. Overall, case NB, where the character did not blink at all, was rated the lowest by all participants. Participants generally agreed that the total lack of blinking was disconcerting. Case R+PGE was rated as the most plausible of the animations by the participants, followed by case GE (gaze-evoked blinking) and case RU (regular unsynchronised).

5.3. Experiment 1: Blinking

Ten participants (5M:5F) from varying backgrounds were shown multiple animations on a 17 in. screen (resolution 1680×1050) of the male character making varying blink motions according to two distance conditions: the near (N) condition used the exact same stimuli from the pilot study, with the virtual character positioned close-up to the viewer, and clearly visible on a light grey background. In the far (F) condition, the agent was placed further away in the virtual environment, and its eyes and blinking behaviour were slightly more difficult to see than in the near (N) case, although still clearly visible.

As before, all head movement were the same apart from the BlinkType, which had five conditions: no blink (NB); regular unsynchronised (RU); gaze-evoked (GE); probabilistic gaze-evoked

Table 2
Conditions in experiment 1: blinking.

Condition	Type	Description
BlinkType		
NB	No blinking	The character did not blink at all during the animation
RU	Regular unsynchronised	The character blinked according to a set interval of one blink every 3 s. Blinks were not synchronised with gaze shifts
GE	Gaze-evoked	The character blinked only when a gaze change took place. The probability of a blink occurring with a gaze shift was set to 1.0, i.e. a blink was made every time that a gaze shift took place, no matter how small
PGE	Probabilistic gaze-evoked	The character only blinked when a gaze shift took place, doing so with a probability given in Section 4.1
R+PGE	Regular probabilistic gaze-evoked	This was a mixture of the probabilistic gaze-evoked and regular cases. The character blinked at regular intervals by default, and also when a gaze change took place, with a probability calculated according to the description in Section 4.1
Distance		
N	Near	The character is displayed close-up to the screen
F	Far	The character is positioned further away in the virtual environment, so that its head and upper torso are visible

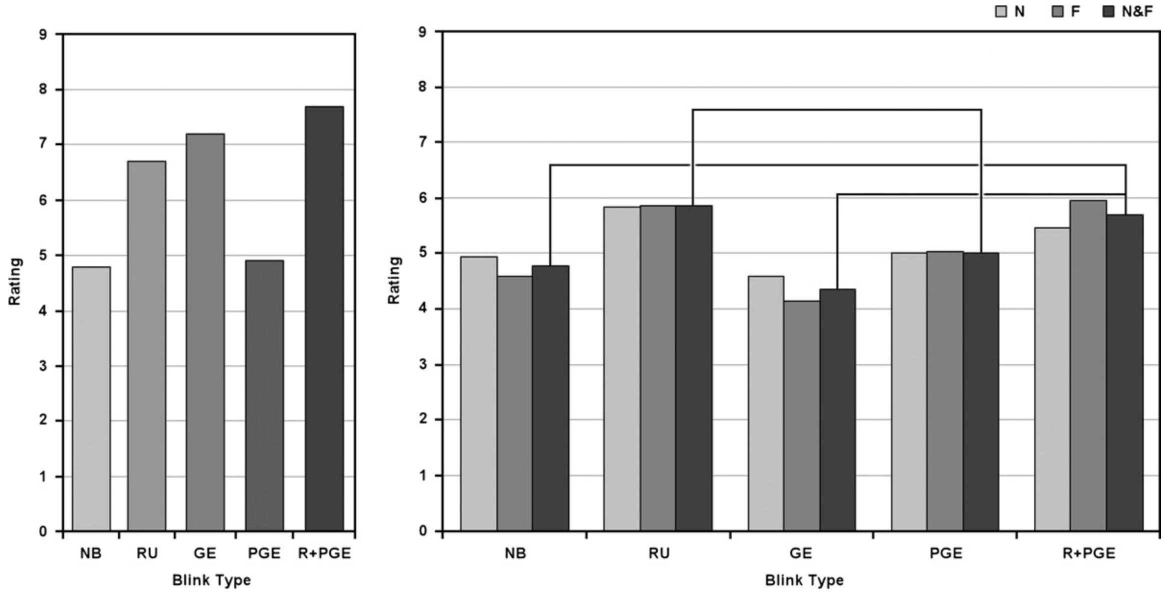

Fig. 8. Left: Mean ratings across all participants ($N=6$) for the pilot study for five blink conditions no blinking (NB), regular unsynchronised (RU), gaze-evoked (GE), probabilistic gaze-evoked (PGE) and regular, probabilistic gaze-evoked (R+PGE). Right: Mean ratings across all participants ($N=10$) for the 5 blink conditions and distance conditions near (N), far (F) and averaged near and far (N&F). Lines indicate cases approaching significance.

(PGE); regular + probabilistic gaze-evoked (R+PGE). See Table 2. Each animation lasted approximately 30 s.

5.4. Experiment 1: results

Two sets of results were analysed: those for the near (N) condition only (Section 5.4.1), and the results of both conditions together (Section 5.4.2). See Fig. 8: Right.

5.4.1. BlinkType: near only

Here, the ratings relating to the near condition (N) were analysed on their own. A repeated-measures ANOVA was carried out, with BlinkType as the independent variable (IV), with five levels: no blink (NB); regular unsynchronised (RU); gaze-evoked (GE); probabilistic gaze-evoked (PGE); regular+probabilistic gaze-evoked (R+PGE). The dependent variable (DV) was the rating of naturalness of the gaze behaviour (on a scale of 0–100).

The results for the (N) condition showed no significant differences between the five blink types ($p=0.510$). Paired-samples t-tests were conducted to compare naturalness of gaze behaviour scores in no blink (NB) and regular, probabilistic gaze-evoked (R+PGE) conditions, and in the regular unsynchronised (RU) and regular probabilistic gaze-evoked conditions (R+PGE).

- There was no significant difference in the scores for the no blink (NB: $M=49.44$, $SD=27.78$) and regular, probabilistic gaze-evoked (R+PGE: $M=54.44$, $SD=28.77$) conditions; $t\ (8)=-1.114$, $p=0.298$.
- There was no significant difference in the scores for the regular unsychronised (RU: $M=58.33$, $SD=28.61$) and regular, probabilistic gaze-evoked (R+PGE: $M=54.44$, $SD=28.77$) conditions; $t\ (8)=0.614$, $p=0.556$.

An analysis with gender as a between subjects IV showed no significant differences in ratings between males and females for this experiment ($p=0.173$).

5.4.2. BlinkType with distance

A second repeated-measures (5×2) ANOVA was used to investigate the effect of the near (N) and far (F) conditions and BlinkType on the naturalness ratings. The IVs were BlinkType, with five levels: no blink (NB); regular unsynchronised (RU); gaze-evoked (GE); probabilistic gaze-evoked (PGE); regular + probabilistic gaze-evoked (R+PGE), and Distance: near (N); far (F). The DV was the rating of naturalness of the gaze behaviour (on a scale of 0–100).

There was no main effect of Distance ($p=0.876$). There was a main effect of BlinkType: $F_{(1,4)}=2.778$, $p=0.043$, $\eta_{p^2}=0.696$. There was no interaction between Distance and BlinkType ($p=0.732$). Pair-wise comparisons indicated that there were no significant differences between BlinkType, but that several approached significance, as follows (see Fig. 8: Right):

- The mean difference between no blink (NB: $M=47.67$, $SE=8.53$) and regular, probabilistic gaze-evoked (R+PGE: $M=56.94$, $SE=9.30$) approached significance ($p=0.084$).
- The mean difference between regular unsynchronised (RU: $M=58.44$, $SE=9.58$) and probabilistic gaze-evoked (PGE: $M=50.11$, $SE=7.34$) approached significance ($p=0.093$).
- The mean difference between gaze-evoked (GE: $M=43.56$, $SE=7.67$) and regular, probabilistic gaze-evoked (R+PGE: $M=56.94$, $SE=9.30$) approached significance ($p=0.052$).

An analysis with gender as a between subjects IV showed no significant differences in ratings between males and females for this experiment ($p=0.177$).

5.5. Experiment 2: head direction/ratio experiment

A pilot study was conducted in order to assess the plausibility of gaze and blinking animations created by the system. Twelve participants (6M:6F) from varying backgrounds, aged between 20 and 50, were shown multiple animations on a 17 in. screen (resolution 1680×1050) of a female virtual character making a series of eye and head movements towards a target (not visible to the participants) at 18° eccentricity (see Fig. 10).

Each trial differed according to the direction of gaze (up, down, left, right) and the HeadRatio (0, 0.25, 0.5, 0.75, 1). The four gaze directions these were collapsed into two GazeDirection conditions: (horizontal; vertical). The HeadRatio described the amount that the character employed its head during a single gaze

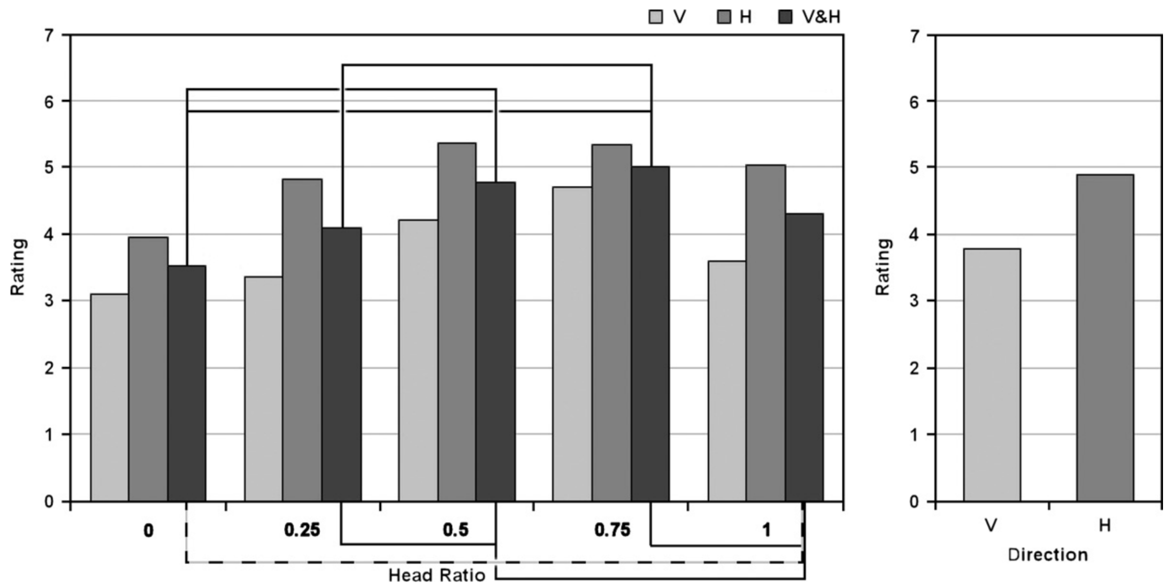

Fig. 9. Left: Mean ratings across all participants ($N=12$) for the 5 head ratio conditions [0,0.25,0.5,0.75,1] for the 2 direction conditions vertical (V) and horizontal (H), and the mean vertical and horizontal values (V&H). Lines indicate significant differences between cases, the stippled line indicates a result approaching significance. Right: Comparison of mean ratings across all participants ($N=12$) and all 5 head ratio conditions for direction conditions vertical (V) and horizontal (H).

motion: thus a HeadRatio of 0 specifies a gaze motion where only the eyes move, and a HeadRatio of 1 specifies a gaze motion where only the head is moved. Intermediate values recruit both the head and the eyes to varying degrees.

Each animation lasted approximately 2 s. Participants were instructed that they would witness a virtual character making gaze motions, and were asked to rate the naturalness of the character's behaviour on a scale of 1–100 at the end of each trial.

5.5.1. *Experiment 2 results*

To investigate whether the direction of gaze and head ratio had any effect on perception of naturalness, a 2×5 repeated-measures ANOVA was used. The IVs were GazeDirection (horizontal; vertical) and HeadRatio (HR0; HR0.25; HR0.5; HR0.75; HR1). The DV was the rating of naturalness of the gaze behaviour (on a scale of 0–100).

There was a main effect of GazeDirection: $F_{(1,10)}=6.296$, $p=0.031$, $\eta_{p^2}=0.386$, with horizontal movement being rated significantly more natural than vertical movement (see Fig. 9: Right). There was also a main effect of head ratio: $F_{(1,4)}=5.275$, $p=0.002$, $\eta_{p^2}=0.345$. There was no interaction between direction of gaze and head ratio ($p=0.782$).

Pair-wise comparisons (see Fig. 9: Left) showed that there were significant differences between the mean head ratios of:

- the 0 head ratio condition (HR0: $M=35.27$, $SE=6.99$) and the 0.5 head ratio condition (HR0.5: $M=47.84$, $SE=6.99$) with $p=0.036$.
- the 0 head ratio condition (HR0: $M=35.27$, $SE=6.99$) and the 0.75 head ratio condition (HR0.75: $M=50.16$, $SE=7.86$) with $p=0.021$.
- the 0 head ratio condition (HR0: $M=35.27$, $SE=6.99$) and the 1.0 head ratio condition (HR1: $M=43.07$, $SE=6.92$) approached significance ($p=0.093$).
- the 0.25 head ratio condition (HR0.25: $M=40.91$, $SE=5.72$) and the 0.5 head ratio condition (HR0.5: $M=43.07$, $SE=6.92$) with $p=0.030$.
- the 0.25 head ratio condition (HR0.25: $M=40.91$, $SE=5.72$) and the 0.75 head ratio condition (HR0.75: $M=50.16$, $SE=7.87$) with $p=0.045$.
- the 0.5 head ratio condition (HR0.5: $M=47.84$, $SE=6.99$) and the 1.0 head ratio condition (HR1: $M=43.07$, $SE=6.92$) with $p=0.032$.
- the 0.75 head ratio condition (HR0.75: $M=50.16$, $SE=7.86$) and the 1.0 head ratio condition (HR1: $M=43.07$, $SE=6.92$) with $p=0.028$.

An analysis with gender as a between subjects IV showed no significant differences in ratings between males and females for this experiment ($p=0.920$).

5.6. *Discussion*

The aforementioned results are discussed here in relation to the research questions at the beginning of Section 5.

5.6.1. *Are some blinking strategies perceived as more natural than others?*

Although the pilot study suggested the possibility of differences in the perception of different blink strategies, results were far more mixed in Experiment 1 (compare Fig. 8: Left and Right). In the near condition (N), while the mean values for cases RU and R+PGE were higher than the other conditions, no significant differences were evident between the different blink types. It is particularly noticeable here that the no blink condition (NB) appears to perform as well as the cases where blinks are present. This seems surprising given the time frame of the animations (30 s). Many participants reported after the experiment that they did not notice any difference between the different animations at all, while others described seeing differences in the movement of the head that were not actually present. Many reported not noticing any difference in the blink behaviour of the character. There are a number of possibilities for these results, in particular the increased diversity of the population in comparison to the pilot study.

When the averaged results for the far condition (F) are considered together with the near condition (N&F), several cases approach significance. Importantly, R+PGE outperforms the no blink (NB) condition. It also outperforms the gaze-evoked condition (GE). Since the character engages in many different gaze shifts during the 30 s sequence of video, it is likely that the

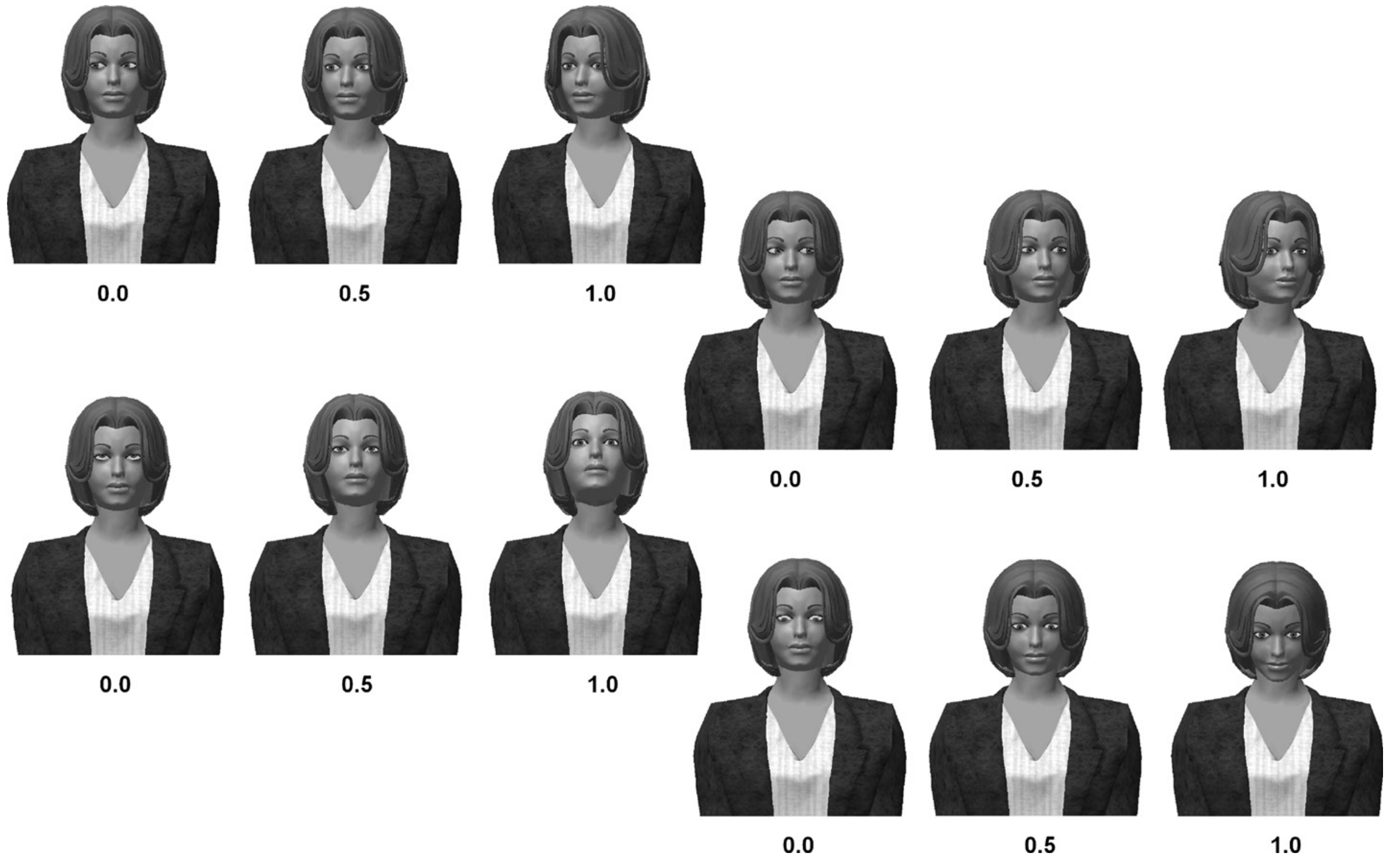

Fig. 10. Example of the stimuli used for the head ratio and gaze direction experiments. Displayed are head ratios 0.0, 0.5 and 1.0 for gaze directions (top) left, right and (bottom) up, down. In the analysis, gaze directions up and down were collapsed to form the horizontal condition and directions left and right were collapsed to form the vertical condition. A head ratio of 0.0 indicates that only the eyes move to the target, a ratio of 1.0 indicates that only the head will move onto the target, while intermediate values involve both eye and head movement onto the target.

GE condition generates blinks far too frequently to be considered natural. The probabilistic component in R+PGE may help to damp the number of blinks, while the presence of the regular component may ensure that too much time does not pass without a blink occurrence. Overall, the results of this question are not conclusive, although they could be seen to affirm that regular blinks, present in both of the conditions that perform better (RU and R+PGE), are an important component in blink perception.

5.6.2. Are some eye–head ratios perceived as more natural than others?

The results of Experiment 2 (see Fig. 9: Left) strongly suggest that some eye–head ratios are preferable to others. Overall, head ratios involving both the eyes and the head tended to be preferred over those employing solely the eyes or solely the head. The condition where the agent only employed its eyes to look at the target was rated lower than all other conditions. This difference was significant in comparison with the 0.5 and 0.75 conditions, and approached significance with the 1.0 HeadRatio condition. It is worth noting that these results are likely to be especially dependent on the eccentricity used in the current study (18°) and it is unlikely that such ratios would always be suitable. One would not expect eye movements to be found unnatural, for example, when gaze targets are very close to the current focus of attention. However, it is possible that for relatively small shifts of gaze, some form of head movement is expected by viewers. This result generally suggests that the thresholds for both movers and non-movers should not be set to extremes: although this will allow for variety, the resultant animations may also be perceived to be unnatural.

5.6.3. Are there differences in the perception of horizontal and vertical gaze shifts?

The results of Experiment 2 found significant differences in the ratings for horizontal movement than for vertical movement (see Fig. 9: Right). An interpretation of this result may suggest an increased sensitivity to vertical gaze movements of the character on behalf of viewers. Another possibility is also that accompanying vertical movements looked less realistic due to an absence of accompanying eyelid and facial movements: in the current stimuli, the eyelids do not close or open to accommodate the movement of the eye. The results of this deficiency may be less noticeable for horizontal eye movements than vertical. Irrespectively, this result seems to suggest that extra care needs to be taken when synthesising vertical gaze movements.

6. Applications

The model presented here is applicable to any domains where virtual humanoid characters are employed, and is of particular use when they must be seen to attend to their surroundings. Interaction situations for serious games and other applications (see Fig. 11) can generally be described at multiple levels of interaction [26] with respect to the viewer. Gaze motions may have different purposes in each:

1. At long range, as an element in an ambient background. Crowd members in the background should be seen to look around and attend to each other and events in their environments.

Fig. 11. Applications of the gaze controller: interaction with embodied conversational agents in (left) a serious game scenario concerning historical events in ancient Rome and (right) an investigation of shared attention based on gaze detection [29].

2. At medium range, where the purpose of gaze motions may be to signal recognition and openness towards opening an interaction with the viewer, or cueing the viewer's attention towards other events of interest in the environment.
3. At short range, where gaze behaviour is an important component in face-to-face interactions, for example, to signalling interest and conversational turn, and also to direct attention towards objects related to the ongoing conversation.

More subtle gaze motions seem particularly suited to short range interactions between the viewer and agent; at greater ranges, for example, blinks and small gaze shifts may not be visible at all. This may suggest that the distance at which the interaction takes place should be considered when applying the head–eye propensity rules: from a greater distance, a bias towards head rather than eye movements may provide more noticeable behaviours and potent cues without reducing their perceived naturalness significantly (e.g., see Section 5).

6.1. Integration

It must be noted that the model presented here is intended as a low-level gaze component: it deals solely with gaze shift commands. Thus, while it does not consider higher-level aspects, such as gaze allocation according to conversational, emotional, or attentional factors, it is intended as a complementary component in such models.

For example, a visual attention model could determine gaze targets within the environment and their priority, and pass them to the gaze model (as conducted in [17]). The gaze shift model should also be compatible with conversational control models, which routinely operate by calculating gaze-at/gaze-away phases. Operationally, these switches are characterised as gaze shifts, and the model proposed here would ideally complement a detailed saccadic eye model operating when gaze shifts are not taking place i.e. during periods of mutual gaze. The expression of cognitive state, such as looking upwards to think, could also be executed as a gaze shift, although the challenge in this case is to choose eye–head ratio values that give this impression to a viewer, rather than, for example, give the impression that the agent is looking up to stare at a salient event. In this respect, more studies such as those presented in Section 5 are required. This is also the case for use in an emotional cases, where multimodal considerations beyond the quality of gaze must be taken into account, e.g., facial expressions. Here, more work is required to acquire mappings between impressions of emotional states and the low-level motion parameters required to achieve them (see for example [20]).

7. Conclusions and future work

A model of gaze and blink coordination for the animation of gaze shifts for virtual characters has been presented. Eye and head contributions to the final motions are based on head movement propensity in order to provide diversity in the animations; blinking is gaze-evoked, with eyelid closure probability and magnitude dependent on head movement amplitude. This paper therefore contributes two important enhancements for consideration in gaze models: variations in head contributions to provide gaze diversity and blink synchrony with head motion for improved plausibility of gaze shifts.

Important issues for future work include emotional considerations and the context of the interaction. Importantly, in the experiments conducted here, participants were not provided with any context for the character's gaze motions: no stimuli of attention accompanied the character on the screen, nor did it react to or consider the behaviour of the viewer. Gaze could be interpreted differently, for example, when it accompanies the sudden onset of a stimulus, in contrast to conversational settings, where it may be used to signal emotional state or to engage in joint attention with a viewer [32].

A further issue is how multiple gaze constraints can be balanced; after all, the eyes can only be in one place at one time. During a conversational situation, where the duration of gaze at the other interactor is vital for signalling engagement and one's will to maintain the interaction, it remains an intriguing question as to how stimuli in the periphery may be attended to, and gaze generation and perception altered according to affective states and displays (see [4]). Ultimately, these factors must all be married in some manner if more believable behaviours are to be produced. It seems likely that the delicate balancing act conducted by humans under these situations can only be elucidated by further experimentation, not only in relation to gaze motions, but also the visual attention and social intelligence mechanisms underlying them.

Acknowledgments

The authors would like to thank Prof. Catherine Pelachaud and the Telecom ParisTech team for the use of the Greta embodied conversational agent.

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