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Assessment of human perceptual sensitivity to physically non-conforming motion in virtual environments

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Abstract Recent advances in neuroscience have shown that the neuropathological disorders are closely related with diseases such as Alzheimers. Those damages are particularly associated with the intermediate visual perceptual processing which can cause the motion perception defects and abnormal visuospatial functions in daily living of patients. In this paper, we propose virtual reality-based assessment tools for measuring human perceptual sensitivity to dynamic erroneous motions, particularly designed to assess possible early stage of brain damages and its associated visual dysfunctions. The main thrust of this paper is on perceptually tuned virtual reality system that can produce realistic natural behavior. The proposed method contains multiple assessment layers to check the awareness of erroneous motion in natural scenes at various severities. Our VR-based game-type environment provides an effective test bed for various dynamic motion-based perceptual sensitivity experiments. Our initial human subject tests show that game-based test environment produces more coherent and consistent data, preferable to survey-based methods.

Keywords Perceptual sensitivity · Physically-based modeling · 3D simulation

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1 Introduction

The human visual system perceives the changes of motion which are essential information to survive in our daily life. The motion perception can be achieved from fundamental and critical functions such as depth perception, timing of events, distinction of entities from their environment, posture control, and so on. The malfunction of motion perception can cause serious impairment, such as the inability to hold a coherent reaction or respond properly to simple environmental changes. For instance, Alzheimer's disease is a progressive dementia defined as memory impairment accompanied by aphasia, apraxia, or agnosia and causes some problems with memory and thinking. Previous research projects have reported various successful assessment tools in visual and static image-based methods, but those were not sufficient to address real-world scenario. Therefore, simple and easy measurement system for human perceptual sensitivity to physically conforming and non-conforming motion is essential for controlled in-depth studies in functional analysis of early stage of potential brain damages. Because the perception from our sensory organs is propagated to our elementary structures to control a body, a correct understanding of perception is critical for all related fields of neuroscience in general.

Virtual reality provides a computer-simulated environment which supports realistic physical presence in the real world and in imaginary world. A VR systems' believability can be greatly improved by adopting real-time physically-based simulation in the scene [1–5]. The perceptual acuity of healthy normal human subjects has been studied extensively in computer graphics and psychology. The resulting consensus shows that there is a surprisingly large degree of error tolerance in our perceptual sensitivity. For instance, we are very sensitive to erroneous human motion. However, when an animation of an artificial object is viewed alone, one can be convinced of its plausibility due to the human brains inability to accurately disseminate the objects' precise and localized behavior. But the tricky part is that perceptual sensitivity fluctuates based on various factors including age groups and the degree of cognitive impairment. Inspired by this condition, we propose a new technique to measure the level of brain damages through virtual reality (VR)-based visual perceptual sensitivity analysis. For instance, a subtle and early stage of brain damage could cause inability to discern physically conforming behaviors from physically improbable movements. In fact, many military personnel who suffer from traumatic brain injury (TBI) complain of visual problems yet have normal eye examinations.

Our research's focus is to develop an immersive 3D visualization and motion analysis system where we can accurately assess a test subjects vision, ability to recognize presented visual signals, and reaction to the given visual information. Ultimately, we are aiming to use it for clinical purposes after rigorous medical validation and verification of mild TBI cases, but we are also envisioning that this VR system could be used to assess individual variances of responsiveness to external sensory excitations and associated reactions for various behavioral and developmental studies including aging and dementia. In that regards, we have identified three specific objectives to realize the goal of measuring human perceptual sensitivity to erroneous motion. First, the VR system should be able to reproduce natural phenomena of various materials such as fluid, gas, and deformable object at real-time rate of 30 frames per second. Second, the system designer should be able to insert physically non-conforming behavior in the current scene without disturbing natural motion of surroundings. Third, the artificial motion control needs to be achieved with simple and intuitive user interface metaphors so that various degrees of erroneous motions can be generated at proper perceptual sensitivity levels.

The remainder of this paper is organized as follows. Section 2 describes the recent work in VR systems, perceptually tuned graphics system and animation. In Sect. 3, we discuss about the proposed system overview and specific issues on perceptually tuned VR system, followed by motion control of deformable structure. Section 4 shows human subject tests on artificial physically non-conforming behavior and sensitivity measurement on healthy normal candidates to validate our proposed system. Section 5 includes conclusion and possible future directions.

2 Related work

VR related researches have been performed actively in various fields such as training, game, simulation, and medical applications. An important issue in this work is that we can inject physically non-conforming behavior at will, and we can control the severity of distortion to our liking.

For implementing VR system, fast and realistic modeling and simulation techniques are essential. Although many successful physically-based systems have been presented, their simulations or animations focused on the plausibility of results rather than accuracy due to limited computational cost. Some earlier researches show that human beings are unable to accurately distinguish any faults in dynamic motions and OSullivan et al. [6] introduced the evaluation system for visual quality of animations from a physically correct motion point of view. Some experiments [7–9] were also carried out to study the perceptual sensitivity of people for the movement of natural bodies, particularly when the bodies and objects are deformable and complex material properties. According to research results [6,10], normal people have a level of tolerance in establishing the error from the visual perception and we present the experiments and results in order to more accurately determine these limits, particularly focused on sensitivity to erroneous dynamic motion in natural immersive scene setting. There are very little studies done on the human perceptual sensitivity to erroneous motion of natural objects especially when the target objects are highly deformable and complex material properties are involved. However, based on the previous studies [11,12], we can postulate that perceptual sensitivity to complex natural phenomena is also limited.

We hypothesize that the lowered ability to discern physically non-conforming behavior is related to the early stage of mild brain damages. To measure if a human subject is sensitive to erroneous motions at various degrees, the VR system should include a mechanism that allows precise control of motion of a specific object in the scene. Motion sketching and relevant interactive technique for controlling and manipulating rigid body simulation are introduced in [13,14]. To achieve a desired motion, they changed initial physical parameters (position, velocity, etc.), so the result of editing affects the simulation globally due to the tweaked fundamental parameters for the entire simulation. James et al. [15] used pre-computation-based data driven tabulation of state space for quick computation of shape and appearance of deformable objects. Their method permits real-time hardware synthesis of nonlinear deformation and real-time user interaction. But the pre-computing process to encompass possible future motions requires a heavy computation and it only covers a small portion of frequently animated modes.

3 Design of virtual reality-based assessment tool

To test an ability to discern physics awareness in everyday activities, we have developed a natural outdoor scene animator where various causality and eccentricity tests are implemented. Causality refers to the ability to detect whether one event causes another. In a natural outdoor scene, a test subject observes various movements in the scene and evaluate the displayed animation to extract causes of the motions. Then she/he has to discover the connections between cause and consequential movements in the scene. Among all the movements, there is an embedded non-conforming behavior which would defy consistent force field in the scene, with varied severity. The test subject is asked to identify it within a pre-determined time period. The varied severity of physically non-conforming behavior can be modeled and animated with controllable dynamics simulation system. For example, a correct cause/consequence would be exemplified with strong wind resulting in strong flag motion in right direction. In such an environment any wavering movement of a flag to an opposite direction is easily detected as a non-conforming behavior. Test subject should deduce strong wind field by recognizing consistent surrounding motions such as gaseous activities, or nearby trees movements. Figure 1 shows an example of a natural scene where a human test subject is assigned to navigate through in which erroneous object motions are presented on the way.

We have used three test parameters to evaluate the perceptual sensitivity to erroneous motion in natural scene: flag movement direction, flag movement intensity, and eccentricity.

Flag movement direction: Based on the external influence, correct direction of motion (wavering of flag) can be pre-determined. A flag movement direction will be artificially perturbed at various degrees and presented in a scene. A test subject is asked if she/he can identify if it is a physically non-conforming behavior or not. Surrounding

Fig. 1 Natural scene in the proposed system display a golf course in an immersive virtual environment. A test subject will be exposed to a predefined navigation through the environments and encounter physically non-conforming movements along the path

motions, including movements of trees and gaseous motions in the air, will be consistent to provide sufficient visual indications of force field. If a test subject identifies only the perfect angle as conforming, it would yield 100 point score. If 90° or more is considered as conforming, the score would yield 0. Same Maximum Likelihood Parameter Estimation by Sequential Testing (ML-PEST) [16] based staircase algorithms are used for obtaining individual thresholds and the score will normalize to 0–100 scale.

Flag movement intensity: Based on the strength of external influence, the severity and range of motion of flag change. The responsive movement intensity should increase proportionally to the strength of external force. Flag movement intensity will be artificially perturbed at various degrees and presented in a scene. A test subject is asked if she/he can identify if it is a physically non-conforming behavior or not. Test environments, assumptions, and procedures are very similar to the flag movement direction test. If a test subject identifies only the perfect intensity as conforming, it would yield 100 point score. If no movement or twice as fast motion is considered as conforming, the score would yield 0. Same ML-PEST-based staircase algorithms are used for obtaining individual thresholds and the score will normalize to 0–100 scale.

Eccentricity: During forward self-movement, such as walking down the street, the environment and objects in the environment take on a pattern of perceived motion that flows radially outward in all directions. This motion pattern that we perceive is referred to as radial optic flow. The center of the expanding motion pattern is referred to as the focus of expansion (FOE). The FOE is determined by the direction of self-movement and the position of gaze, adapted from Tetewsky et al. [17].

3.1 Perceptually tuned VR system

To develop a realistic virtual environments, we have developed a physics-oriented dynamic system based on Unreal game engine platform [18] on which new features are added as external plug-ins. Unreal is particularly well suit for developing outdoor natural scenes, because it contains tools for creating visually appealing terrain models, particle effects, trees, and vegetation for background scene. World Machine Modeler, a terrain generator and editing tool, is used to generate virtual landscapes and realistic 3D terrains. To incorporate very convincing and realistic natural outdoor scene animation, fluid simulation and vegetation modeling should be incorporated on top of the above-mentioned dynamics system. As fluids are everywhere around us, they are an important part of physical simulation for virtual environments. Numerical simulations of fluid flow have been used for a long time in the field of computer graphics, although mainly for off-line animations. Our method will be an extension from the real-time GPU implementation of a level-set-based fluid solver [19] for stability, controllability, and high performance in numerical computation. One of the crucial components for realistic animation of natural outdoor scene is effective modeling of vegetation and fast animation of tree movements. The complexity of animating trees and shrubs and foliage is an impediment to the efficient and realistic depiction of natural environments. We use physics-based tree animation algorithms based on [20,21] as shown in Fig. 1

to emphasize more on the controllability to suite our test algorithms needs. Our simulation system is a combination of our own constrained deformable mesh simulation (for accuracy) and point-based dynamics system (for fast computation and stability) provided by NVidia PhysX and Apex APIs [22] . We also utilize Speed Tree Modeler [22] to create various forms of plant life influenced by wind for virtual animations in real time. Since the physically non-conforming object, the main object of interest in perceptual sensitivity analysis, should be precisely controlled by the system, it is treated independently using our controllable simulation model described below.

3.2 Controllable simulation

To effectively utilize tests for perceptual sensitivity to erroneous motion, we should be able to precisely control the entire animation, not only the physical input parameters that governs the movement of objects but also direct manipulation of end result such as collision resolution, trajectories and velocity of motion, and specific movement patterns. Quite often, users want to ask many what if questions to a particular simulation that may have different constraints, initial conditions, and various combinations of coefficients. Users should be able to utilize the simulation as a problem solving platform by experimenting diverse simulation situations without major modification of the simulator. Existing approaches in deformable object simulation are mostly based on the passive dynamic simulation where initial parameters are setup in the front and the displacement of nodes are computed from given external forces. Because of the nature of the passive simulation, the result of the simulation is very sensitive to the choice and quality of initial parameters [23]. Under the current passive dynamic simulation paradigm, small changes in the initial parameter result in drastically different behaviors in the end. It is very difficult to predict if the final behavior will be what was desired for the simulation and virtual reality purposes and it is even more challenging to control the dynamic behavior. Controlling the dynamic behavior to the users liking, especially in an interactive platform, is very challenging since it requires a sophisticated algorithms that steer the simulation by issuing and manipulating control forces and force fields in the neighboring structures on the fly. The main goal on this topic is to generate automatically a set of appropriate control forces from user interaction metaphors, such as stopping a simulation and dragging a part of the object or interactively defining the trajectories of nodes. First, a user defines a desirable behavior using predefined path generation tools and it is later converted into a set of small nodal displacements. Then the displacements and trajectories are transferred to a set of space-time constraints that will be enforced in the next running cycle of simulation. So the main idea is to stop the simulation whenever and wherever a user wants, and to steer the simulation to test different scenario on demand. We extended our controllable dynamic system to affect the underlying simulation using a set of external control parameters, and the specific algorithms are tailored to suit this project scope [24]. The physical system equation of movement of discrete masses with external control forces is $M\ddot{q} = F + u$ where F denotes applied, gravitational, damping, and other relevant forces acting on the discrete masses, while u being the control parameter. The equation of motion along with the kinematic relationship between q and $\dot{q}$ is discretized as

$$\dot{q}_{n+1} = \dot{q}_n + \Delta t M^{-1} F_n + \Delta t M^{-1} u_n \tag{1}$$

$$q_{n+1} = q_n + \Delta t \dot{q}_{n+1} \tag{2}$$

Substituting $\dot{q}_{n+1}$ in Eq. (1) into Eq. (2), we get (3) and (4) to calculate control parameter u

$$q_{n+1} = q_n + \Delta t \dot{q}_n + \Delta t[\Delta t M^{-1} F_n + \Delta t M^{-1} u_n] \tag{3}$$

$$u_n = M\{q_{n+1} - [q_n + \Delta t \dot{q}_n + \Delta t^2 M^{-1} F_n]\}/\Delta t \tag{4}$$

Our system tries to generate the new motion path $q*$ using the heuristic optimal method, computed by the control forces described in Eq. (4) [25].

3.3 Deformation control user interface

To alter the motion of a deformable structure like a cloth or soft body to the exact designated form, an effective user interface control mechanism is important. It is particularly relevant to the controllable simulation where we need to inject a specific physically non-conforming behavior which is not possible through a conventional control method. In this implementation, we use widgets which we define as sphere, twist, bend, flatten, squash, and stretch. These widgets, metaphorically speaking, actually can produce edge rounding, deflection, or other indirect motions than what the name portrays. This is because applying a control force to an object in a localized manner leaves great flexibility as to how the smaller region of the object interacts with the overall structure. For example, the flexible end corner of a flag moving through space may exhibit natural flopping, twisting, or bending; however, when we apply a bending metaphor we may actually see a linear projection since the base of the flag is anchored in a much larger mass structure. In a similar respect, if we use the spherical widget on the corner of a square shape we will actually see a rounding of the edge instead of a direct mapping to a sphere. We see these indirect motions and specific pose behaviors; thus we have termed this the behavior-based pose-metaphor.

3.4 Human perceptual sensitivity measurement method

The primary purpose of the VR system is to put a group of human subjects to see if we could find a meaningful pattern in perceptual sensitivity to erroneous motion in the scene. This could be a battery for the assessment of brain function especially when the human subject is a candidate for an early stage of mild brain injuries. In this paper, we focus on the assessment tools and measuring threshold using psychophysical methodologies.

All participants are instructed for the overall procedures of experiment and the operator explains the details of controller device for virtual reality test. First, participants answer some primitive survey questions such as their name, gender, and educational background, and other personal questions. Then the objectives of the experiment and observed trails are introduced by an operator. They are also exposed to several practice runs of virtual environment to be familiar with them. In this study, two threshold measurement methods are used; the staircase method and two alternative forced choice (2AFC) [26]. The staircase method is a modification of the Method of Limits [26,27]. In this procedure, the order of presentation of trials in the stimulus array is determined by responses provided by the participant to the one or more trials that were presented previously. Therefore, after initial trial, the participants reaction determines the parameters of next trial in sequential manner. Simple up–down adaptive staircases involve a decrease in stimulus strength of subsequent trials in a stimulus array when a participants response is correct, and an increase in stimulus strength following an incorrect response, similar to a binary search. In these procedures, the first trial of an experimental block contains a target stimulus, and consecutive correct responses by the participant lead to continued reduction in stimulus strength, until an incorrect response is made, then the stimulus strength is increased.

This type of measurement method fits well for a case where participants can respond to the stimulus with definitive choice. Alternatively, we experimented two alternative forced-choice method (2AFC) where two stimuli are presented in randomly selected order. After both intervals have been presented, the participant must indicate whether the stimulus was present in the first interval or the second interval was proper for the question identified earlier. For example, they would be asked which one is physically more convincing between those two. The magnitude of the stimulus may or may not be modified for the next presentation. Forced-choice methods require participant to make some judgment about which interval from within a limited set of alternatives is the target stimulus. The participant has freedom to go back and forth between the two choices until they are certain for their answers. This method works well for a physically non-conforming behavior where the severity of the non-conformity is not particularly significant. Hence it helps us to find more precise outcome typically unobtainable from the staircase method. We use the staircase method for initial trial and repeat the same sets of trials with 2AFC for further analysis. This pair of experiments makes a set and three sets are repeated per each test subject.

4 Experimental tests and results

For experimental human subject tests, we recruit twenty young healthy and normal people as volunteers. The participants consisted of 12 males who aged from 22 to 34 years and 8 females who aged from 23 to 27 years. The average age is 26.5 years and they did not have any histories of mental illness. They have limited experience in virtual reality setup but they are well acquainted with the human computer interaction devices. Moreover, they have sufficient mental faculties of insight for their circumstances.

Test subjects are exposed to outdoor natural environments similar to real everyday activities, such as walking on a park, as shown in Fig. 3. Various natural objects are moving under the influence of natural phenomena, such as wind. A particular object is defying physics and displaying non-conforming behavior, i.e., flag is wavering toward incorrect direction of wind at artificially altered speed. We use three test parameters to evaluate the perceptual sensitivity to erroneous motion in natural scene: flag movement direction, flag movement intensity, and eccentricity. A test subject is asked if she/he

Table 1 Levels of severity for 0–180° test

Category	1	2	3	4	5	6	7	8
Degree separation	22.5°	45°	67.5°	90°	112.5°	135°	157.5°	180°

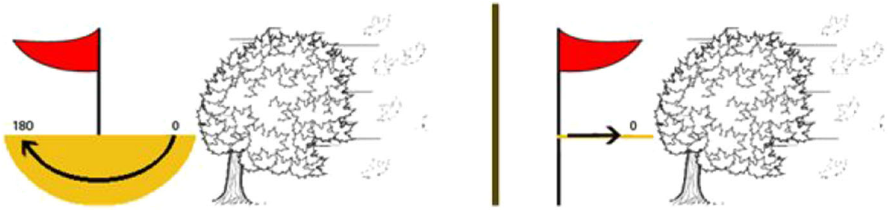


Fig. 2 2D side-view demonstration of 180° severity category. In the *left* picture, the motion of trees suggest that the wind direction is from right to left, but the *flag* shows a completely opposite direction of motion. The *flag in the right* picture shows conforming behavior

can identify if it is a physically non-conforming behavior or not. Surrounding motions, including movements of trees and gaseous motions in the air, are consistent to provide sufficient visual indications of force field.

The first experiment was to find physically non-conforming flag movement when its influenced by wind. Participants observe the entire scene and they should aware windy environment by observing movement of trees, gas from a chimney and other indicators. They are to detect if the flag is erroneously moving when its wavering direction is artificially altered at varying direction from 0° to 180° apart. Table 1 shows how angles from 0° to 180° are categorized in 8 groups at 22.5° apart.

Initially participants complete the staircase test with a series of single scene, followed by 2AFC. For 2AFC, test subjects are presented with two scenes with slightly different wind directions and they are asked to pick a visually conforming one. Typically those two presented scenes are very similar except that they are different in wind direction angle. One of them (no particular order) has exactly right movement based on the current wind direction while the other one includes a deviated fixed angle from the exact angle, resulting in physically non-conforming behavior incurred by the intentionally distorted condition. In this experiment, the severity of the distortion is dictated by the amount of angle of deviation of wind. The varying degrees of the angles are controlled by the severity controller. The severity controller has eight values categorized as shown in Table 1 from narrow angles to wide angles. In practice, test subjects report that it is not easy to discriminate conforming behavior with narrow angle differences, but its quite obvious to detect cases beyond 120°.

Figure 2 shows an example of 2D first level in severity category. Within each trial, the stimuli are presented in two different scenes for the subject to switch between them using two arrow buttons with controller which can represent right and left. The time interval between stimuli is 5 s. After viewing the two stimuli, subjects report their judgments by pressing one of the two designated buttons on the computer keyboard. A new trial begins one minute after the subjects response is recorded. The snapshot of implemented VR-based human perceptual sensitivity measuring tool is shown in Fig. 3.

Fig. 3 snapshot of the proposed human perceptual sensitivity measuring tool using VR

Fig. 4 Results of threshold estimation for all participants (0–180°)

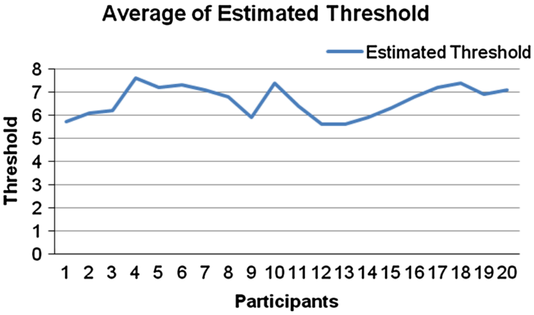


Table 2 Results of one of the participants using constant stimuli at varying degrees

Stimulus intensity	0 – 10°	10 – 20°	20 – 30°	30 – 40°	40 – 50°	50 – 60°	60 – 70°	70 – 80°	80 – 90°
Perceived stimulus rate out of 20 trials	1	3	6	11	14	17	20	20	20
Percentage of correct answer	5	15	30	55	70	85	100	100	100

Figure 4 shows our participants overall threshold estimation score of 6.62 on average. The result indicates that the threshold values of participants are between 5.60 and 7.58 and it represents the range from level 6 to level 7 of correction. In other words, they were not able to distinguish narrow angle difference but everyone was able to identify physically non-conforming flag behavior if the wavering direction is beyond 120°.

The second experiment is designed to narrow the angle differences to 0–90° since there was virtually no failure rate beyond 120°. In this case, degree separations are divided into 9 groups at 10° apart. Table 2 shows one participants percentage of correct identification of physically non-conforming behavior.

Each participant went through 20 trials and Table 2 shows their responses and successful identification of physically non-conforming behavior in the scene. Figure 5 shows individual psychometric functions to get each ones threshold from the proba-

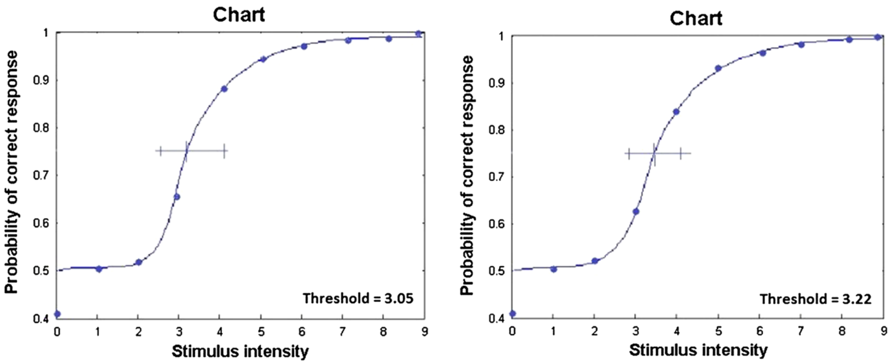
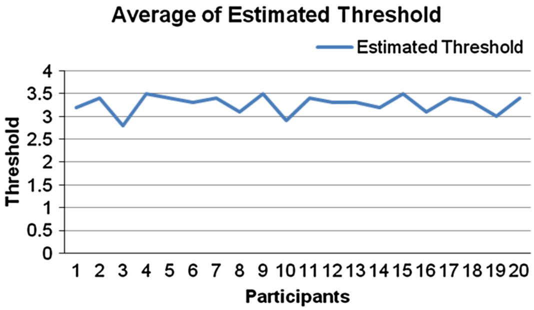


Fig. 5 Two participants' probability of correct respond on erroneous flag motion from 0 to 90° deviated from physically correct direction

Fig. 6 Average of estimated perceptual sensitivity to erroneous motion for 0–90° test



bility of correct response. As shown in Fig. 6 the average threshold of all participants is 3.27, which indicates that all the young healthy participants were able to detect physically non-conforming behavior when the wavering flag angle is bigger than 35° away from correct behavior and when the angle is below 20° it is hardly identifiable.

This test result suggests that healthy young people can successfully distinguish physically conforming and non-conforming motions from a natural scene within a reasonable margin of error bounds. The flag movement intensity tests also showed similar threshold patterns, but eccentricity does not portray a clear pattern and therefore, we believe its inconclusive given current setup without head and eye tracking system involved in the study. We hypothesize that if this test is applied to patients with mild brain damage, it would give lower percentage of threshold estimation.

5 Conclusion

In this paper, we have proposed a VR-based assessment system for testing the human perceptual sensitivity from the flawed movement in order to study the primal indications of brain function. The proposed system is aimed to measure the test subjects sensitivity from physically confirming to non-confirming motion in a natural and composite scenario. For this purpose, an outdoor environment is created and loaded with artificial as well as natural motions made with physics-based simulator. The simulation system is designed to address perceptually tuned animation in a real-time virtual environment in which the artificial movements defying physics laws are implemented through an intuitive controllable simulation scheme.

The results of our experiments show that perceptual sensitivity of physically conforming or erroneous motion can be clearly detected within a logically firm band from a group of healthy young people. Based on our experiments, it is considered to be a good initiation for the later full-fledged clinical experiments for a group of mild traumatic brain injuries who may have lowered ability to detect physically non-conforming behavior as healthy normals. Although the proposed method is not able to completely analyze the body reaction and gestures of the subjects based on the response to the external factors, we believe that it could be the future directions for study that have yet to be addressed. For the future study, the algorithm can be improved by adding optic flow to do a predictive detection of several scenarios linked with the real natural scenarios and we can apply the efficient database design or data analysis technique [28] for assessment of human perceptual sensitivity as well.

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