

Video Game Design Using an Eye Movement Dependent Model of Visual Attention

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1. INTRODUCTION

As the accessibility and accuracy of eye tracking systems has improved, more and more research and systems applications have taken advantage of the benefits of monitoring eye movements. Eye tracking has been extensively used in the study of visual attention, due to the close relationship between attention and eye movements. Research on eye movements show that eye movements reflect human thought processes; this led Yarbus to suggest that an observer's thought may be followed to some extent from records of his or her eye movements [33].

Most current visual attention models ignore top-down influences, focusing only on bottom-up information in the processing of natural scenes. The saliency model of attention proposed by Koch, Itti, and their colleagues used bottom-up information of scenes to indicate the possible locations of attention [11]. It is, however, well known that scene context and task strongly influence attention [32; 19; 28; 14; 29; 10; 21].

It is even more important to consider top-down factors of attention when estimating attention allocation for applications, such as human computer interface (HCI) and entertainment devices, because attention is more task-relevant and goal-driven for these interactive interfaces than for free-viewing of scenes. Except the fact of ignoring the task-dependent effects, the work done only consider saccadic eye movements. This is far from enough to take advantage of using eye movement information for attention detection.

Previous work has been done regarding to either the study of attention patterns during different types of games or the method used to attract attention [3; 2].

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However, none of them consider analyzing top-down factors of attention using eye movement information and apply the attention analysis to a game design. In this paper, we propose a new way to estimate task-dependent attention allocation based on eye movement information besides saccades (specifically detecting fixation and pursuit conditions). Combining such eye movement information with image information at eye fixation points, and transient locations during pursuit, we present a simple way to estimate to what extent attention is engaged at a fixation point. Based on the estimation of the location and strength of attention allocation, we show how an interactive computer game can be designed to exhibit different difficulty levels. The game is used to support our hypotheses concerning attention and demonstrates the benefits of using eye tracking information as an input to game design. The feasibility of applying these ideas to the design of a computer game suggests that they can be applied to the design of more intelligent HCI and other interactive machines as well.

In order to use the knowledge of attention in game design, top-down factors of attention must be considered, since attention is more task-relevant and goal-driven for game playing than for just free viewing of scenes. Task dependence is a very complex issue, as there are a large number of cognitive tasks that a person can be engaged in, even in an activity as focused as game playing. To simplify the problem we will consider just two rather general classes of task - those that involve having the eye fixed at a specific location (fixating) and those in which the eye is tracking a moving target (visual pursuit). As such, we will examine the allocation of attention in each of these two conditions.

Tracking of moving objects with the eye is needed in many different computer games. Conversely, many game situations require the eye be fixed at a given spot, in order to extract information from that spot or to wait for an expected event. Thus, it is necessary, and rewarding, to consider attention based on the specific motion of the eye. Recent studies [30; 12] have shown that during ocular pursuit, the allocation of attention in space is found to lead the pursuit direction (i.e. in the direction of object motion). The distance by which attention leads the eye is observed to increase as the pursuit velocity increases. Thus, if we know that the eye is undergoing a pursuit motion we can predict that the attention is most likely to be allocated at some distance ahead of the motion.

In the case of eye fixation, we consider two important aspects. The first is consideration of where the gaze tends to be directed (the fixation point) and the second is consideration of how long the gaze remains at the fixation point (fixation duration). There has been much work done regarding the location of fixation points [27; 13; 23]. But apart from specialized studies on eye movements during reading [25], relatively little research has been aimed at understanding fixation duration during scene viewing. The prediction of the distribution of attention can be markedly different based on different predictions of fixation duration. In this paper, we will explore a way of relating fixation duration to scene complexity.

The issue of fixation duration is, in our view, the problem of how tightly attention is “glued” to a fixation point once the fixation point is chosen. The problem has been studied [10; 24; 9; 15; 16] and combined into models of reading [25]. But for computational attention models of general scene perception, it has been neglected.

The well-known saliency model of attention relates fixation duration to the saliency value at fixation points [11], incorporating features such as scene luminance [15] and contrast [16]. Fixation duration has also been found to be longer when viewing face images [8] and color photographs [9]. All these studies suggest that fixation duration is influenced by the processing of information presented at the current fixation point. But saliency only tells part of the story. Not only bottom-up but also top-down attentional factors are involved in determining fixation duration. The saliency value may give clues of where attention or the gaze is directed at the beginning of viewing a scene. But once fixation begins, for the duration of the fixation, we believe that the processing of the information of image at the fixation point is more important than the raw saliency at the fixation location. In particular, we take as a simple model that the fixation duration is related to the complexity of the image or scene at the fixation point, as a higher complexity implies that the brain requires a more detailed processing of the visual input to make sense of the scene. For the purposes of computer game design, we hypothesize that local measurements of fixation point scene complexity can be used to predict the “stickiness” of attention, which will affect the speed at which attention can be shifted away to new targets, and hence will affect reaction times.

To study these two task-dependent aspects of the attention related to eye movements (i.e. fixation duration and attention during pursuit) we carried out a set of psychophysical experiments. These experiments tested the effect of (in the fixation case) image complexity on reaction time and (in the pursuit case) the relative location of target transient visual stimuli on reaction time. The results obtained during the experiments were then applied to an interactive 2D computer game to make the game easier or harder through controlling the position of game elements based on our attention models. Consistent results were shown. The idea of designing games, using eye movement information as an input, taking into account of attention characteristics during different tasks was demonstrated.

2. EXPERIMENTAL METHODS

2.1 Experiment procedure and apparatus

The purpose of the first experiment was to determine the extent to which image complexity at the fixation point affected the disengagement of attention during fixation and pursuit conditions.

The visual stimuli were generated by a computer and displayed on a screen of a 1280*1024 pixel monitor at a distance of 18 inches (1 degree of visual angle corresponded to approx 30 pixels). Five hundred color images (640*480) from different scene categories (landscape, building, city scene, indoor scene, animal, etc) were used as background. Figure 1 shows a representative sample of background images from the set of 500 images that were used in the experiments. At the beginning of each trial, a fixation mark of size (0.26*0.26 deg) appeared at the center of the monitor. The background of the monitor was set to be black at this time. After participants centered their fixations on the fixation point, and felt ready for the experiment, they initiated trials with a key-press. Once participants triggered the trials, a background image was shown, centered on the display. One small green square of size (0.26*0.26 deg) started to move either rightward or leftward



Fig. 1. Examples of images used as background for the experiment. Each column represents one category of images. From left to Right: city scene, landscape, building, animal, and interior scene.

at a speed of 1.4 deg per second from the center of the background. Participants were instructed to either pursue the moving square or freely view the background images. Approximately 2 seconds after the start of every trial, one square object of size (0.65*0.65 deg), colored either green or blue, appeared at random positions over the background images. Participants were required to react to the color of the square object as soon as possible by pressing corresponding mouse buttons.

Six participants (five males, one female) participated in the experiment. The participants were all graduate students. Data was collected after informed consent was obtained. Experimental sessions lasted for approximately one and a half hours with mandatory three-minute rest periods occurring after approximately every five minutes of data collection. Participants were given practice in performing the task before collecting experimental data. Participants had control over when to start a trial through the pressing of a keyboard button. They were seated approximately 18 inches away from the display, and a chin rest was used to minimize head movements. An eye tracker (ISCAN RK-726PCI) was used to record the participants' left eye positions at 240HZ during experiments. The eye tracker's vertical resolution is approximately 0.11 degrees and its horizontal resolution is 0.06 degrees. A CRT monitor was used for display. Participants used both eyes to conduct the experiments.

2.2 Data analysis of eye positions

At the beginning of every experimental session, we calibrated the eye tracker by having participants look at a five-point calibration display. The extended visual angle for the calibration is 10 degrees for every direction. Because we used the images whose sizes are 640*480, the each side of the images were inside of the 10 degrees area. For the right and left sides of the images, they are about 10 degrees away from the center of the display. For the top and down sides, they are about 8 degrees away from the center.

Data analysis was carried out on every single trial. By visual inspection of the individual recordings, trials with blinks before the appearance of the flashed square

object, missed pursuits, or missed executions were excluded from further analysis. For free viewing trials, trials were excluded if the flashed square object appeared within the same area as previous eye fixation locations. Each channel of eye position data were smoothed with a 9 point median filter.

After the data analysis, over 1000 cases of data for fixation and pursuit eye movements were gained separately for further analysis and obtaining results.

2.3 Entropy of images

To quantify how much information (image complexity) is present in the background image at the fixation point, we used the entropy of the normalized image histogram in a neighborhood of 3 degrees square around fixation point. We will refer to this as the information quantity.

The choice of using entropy is motivated by the study of the relationship between image contents and fixation locations in the literature [22; 17; 18; 20; 31] and the characteristic of entropy as well. In general, entropy can measure the contained information quantity as required by us. To validate that the measures of entropies can well complete our request, we compared the local entropies of sample images to the number of divided regions of the corresponding segmented images. Because the divided regions represent distinguished image contents, the more the divided regions (more image contents) are, the higher the entropy is. An example of this can be seen in Figure 2, averagely with 5 divided regions, the entropy is about 1 and with 13 divided regions, the entropy is about 4.

As a pre-processing step, a segmentation of the image at the fixation point was first computed using the method proposed in [5]. This is a process to classify each image pixel to one of the image parts, and reduces noise. After segmentation, the color pixel data were converted to gray-levels. Given the human visual systems “preference” for luminance information, the gray-level values were obtained by the luminance of original images. Entropy was therefore computed over the segmented images using the luminance values (Y), obtained from the (RGB) values by the formula $Y = 0.299R + 0.587G + 0.114B$. The entropy was calculated according to formula 1 (P_i represents the probability of the i th level of luminance (range from 0 to 255)).

$$Entropy = - \sum_{i=0}^{255} P_i * \log_2(P_i) \quad (1)$$

3. RESULTS

3.1 For the free viewing condition

The relationship of participant reaction times to both the local image entropy in a neighborhood about the fixation area and the global image entropy over the whole image were checked. An example of high and low entropy patches of fixation areas are given in Figure 2.

Figure 3 shows the mean reaction time (to the flashed square object) as a function of the local image entropy at fixation area and image entropy of whole image separately. As expected, we observed the tendency that reaction time increased as the image entropy at local fixation area increased. But for the global image entropy



Fig. 2. Example of the background image after segmentation process, and the corresponding high and low entropy eye fixation areas. The top left image is an original background image. The top right image is the corresponding segmentation image. The bottom left image is an example of high entropy eye fixation area (entropy value is close to 4) and the bottom right image is an example of low entropy eye fixation area (entropy value is close to 1). These two eye fixation areas are corresponding to the area within the black frame in the top right image respectively.

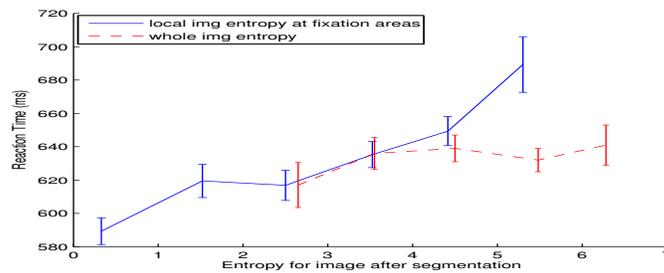


Fig. 3. The relationship between the image entropy and reaction time during eye fixation. Error bars represent standard errors of the mean (same for the following figures).

over the whole image, no such tendency was observed. This indicates that the local entropy at the fixation area is a factor related to the time of disengagement of attention at fixation points.

The corresponding local entropies of target positions are measured as well. In Figure 4, we show the entropies of fixation areas and the corresponding target positions. We can see from this figure that the entropies at target locations have a much slighter tendency to increase compared to increases of the entropies at fixation points. According to the work done by Geisler and colleagues that attention is biased towards high entropy regions [22], so a tendency of decreasing reaction times should be observed based on the analysis of entropies at target locations. However,

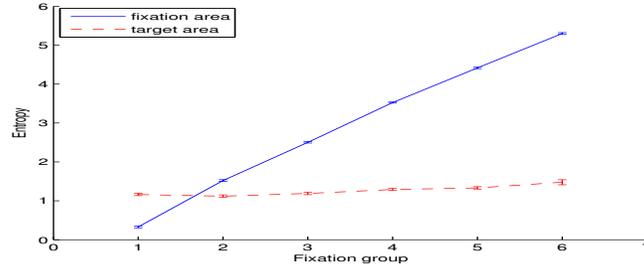


Fig. 4. Entropies for fixation areas and the corresponding target positions. Fixation groups are separated according to their entropies of fixation areas.

an opposite result is seen. So the possibility that not the fixation area entropies but the target position entropies contribute to the different reaction times are ruled out.

According to the result shown in Figure 3, we separated data into two groups, a low local image entropy group and a high local image entropy group. The low entropy group included cases in which the local entropy at the fixation area was less than 3.0; the high entropy group included those cases in which the local entropy was higher than 3.0. The average local image entropies for the two groups are shown in Figure 5. Saccadic eye movements appearing after the onset of the flash but before manual responses were analyzed for both groups separately. Figure 6 shows the latency distributions of the saccades for the two groups. As can be seen from the figure, saccades started approximately 200 ms after the flash onset. Moreover, a bimodal saccade distribution was observed for the high local image entropy group. The second peak appeared approximately 350 ms after the onset of the flash. We refer to these saccades as long latency saccades. After further investigation of the long latency saccades, we found that most of them (approximately 95%) were the second of a sequence of two saccades, in which the first saccades were of normal latency (about 200ms). Most of these long latency saccades were also found to be in the same directions as their leading ones, which were directed towards the flash locations. However, very few sequential saccades were found for the low image entropy group. These secondary saccades could be an indication that the targets for the initial saccades were poorly defined by the saccade planning process, therefore requiring a secondary "corrective" saccade. The imprecision in targeting could reflect reduced attentional resources available to locate the target when the fixation point is in a high entropy neighborhood.

When considering both the reaction times and the saccade latencies together, we can understand why the reaction time tended to increase in the condition of high local image entropy. For the high local image entropy cases, more sequential saccades were needed before giving correct responses. Saccades were triggered by the appearance of the flash as a transient, attention-grabbing stimulus. However, when the local image entropy at the fixation point was high, the competition between bottom-up attention and top-down attention becomes more intense. The cost of the intense competition was the high reaction times. Moreover, some second sequential

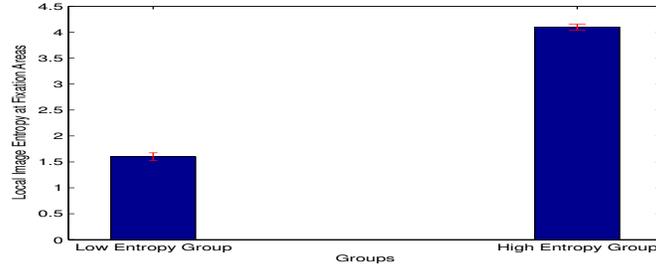


Fig. 5. Local image entropies for low and high groups respectively.

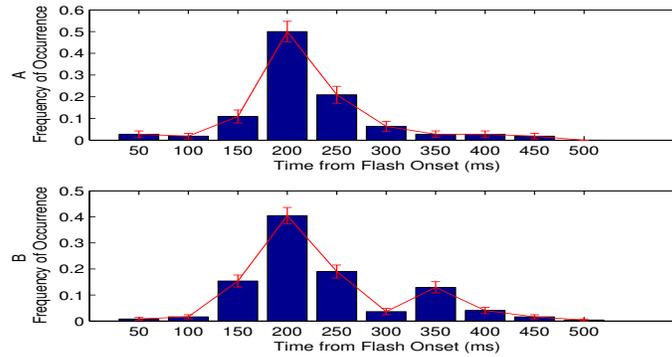


Fig. 6. Normalized saccade latency histogram. A,B are for the low and high entropy groups separately.

saccades were observed between the onset of the flash and the responses. This caused high reaction times as well. When the local image entropy at the fixation point was low, the influence of bottom-up (image-driven or reflexive) attention predominated, which led to lower reaction time. In addition, fewer sequential saccades were observed in this condition, further lowering average reaction times.

The distinction can be seen more clearly when we separate saccades in high local image entropy cases into two groups. One group was for cases in which only one saccade occurred between the onset of the flash and the reaction. The other group was for cases in which two saccades occurred. Reaction times for these two groups and for cases of local low entropy were compared. Results are shown in Figure 7. It can be seen from the figure that the reaction time was higher for cases with two saccades than those with one saccade. Lower reaction times were observed for the low local image entropy cases than for the high local image entropy cases with one saccade.

3.2 For the pursuit condition

The same factors were checked in the pursuit condition. In this case, however, no consistent relationship was found between the image entropy at the eye position

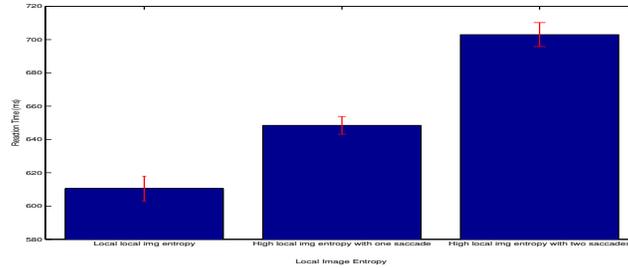


Fig. 7. Reaction time comparison. The local image entropy for the three groups are 1.6(s.e.m=0.07), 4.06(s.e.m=0.06), 4.22(s.e.m=0.15).

and the reaction time. Results are shown in Figure 8. For the case when the visual transient appeared in front of the pursuit direction, the image entropy of the whole image showed a tendency to affect reaction time. However, this was not found for the case when the flash appeared in the opposite direction as pursuit.

Following the experiments described in [30; 12], the reaction time was compared under two different conditions. These conditions are where the flashed object appears ahead of the pursuit direction and where the flashed object appears in the wake of pursuit direction. The results for the comparison of reaction time in these two conditions are shown in Figure 9. From the figure, we can observe that the reaction times for two pursuit cases are significantly different (Ttest, $p < 0.02$).

Also the reaction time for the fixation condition described above and the pursuit condition are compared in this figure. Reaction times are close to each other for the case of fixation and the case of flash behind the pursuit direction, and significantly larger than when the flash occurs in the direction of pursuit. This result is consistent with what was found in [30; 12], where attention was observed to be biased towards the pursuit direction. The bias offset is related to pursuit velocities. The faster the pursuit velocity is, the further ahead attention tends to bias.

We see from these results that the image content at fixation points is more important in affecting attention allocation for fixation than for pursuit. In the pursuit condition, the relative position between the pursuit direction and the visual disturbance is more important than image content.

4. GAME APPLICATION

The results obtained from the previous experiment were applied to an interactive PC game. The game was designed as a normal PC shooter game, except that during the game, eye position information was recorded and analyzed. The eye tracker information was used to determine whether the eye was fixated or was engaged in visual pursuit. This was then used to adjust the strategy employed to present game elements.

The game was designed to exhibit two difficulty levels, hard and easy. For the hard level, enemies were designed to appear at locations of high attentional cost. For the easy levels, enemies were designed to appear at locations with attentional benefit. For the hard level, enemies were displayed when the eye was fixated at a

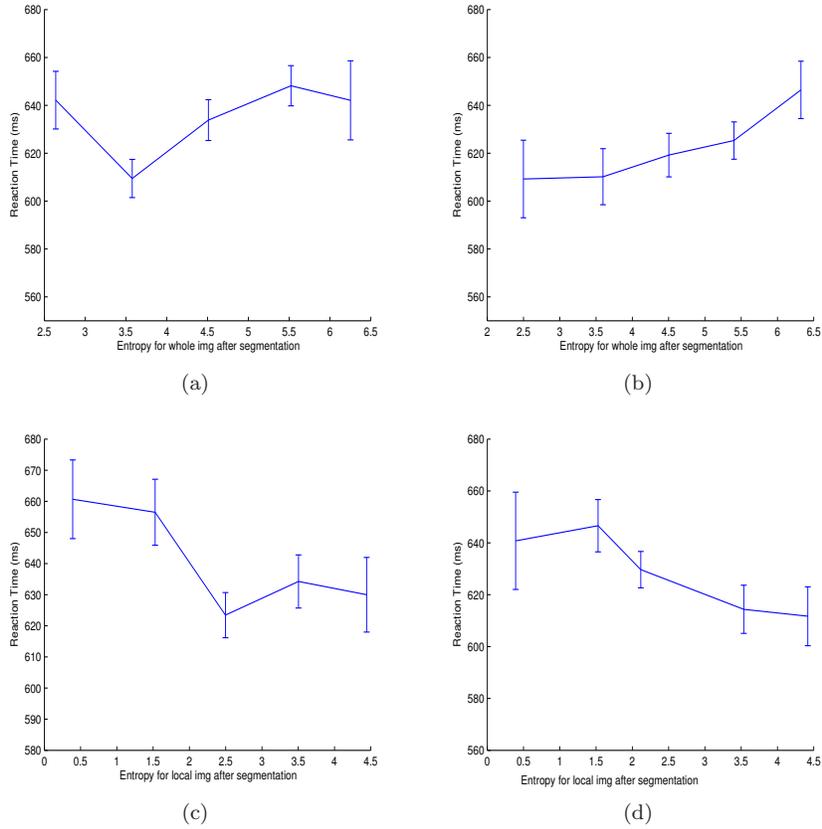


Fig. 8. Relationship between image entropy and reaction time during eye pursuit. (a) Relationship between the whole image entropy and reaction time. The flash appears behind the pursuit direction. (b) Relationship between the whole image entropy and reaction time. The flash appears ahead of the pursuit direction. (c) Relationship between the local image entropy and reaction time. The flash appears ahead of the pursuit direction. (d) Relationship between the local image entropy and reaction time. The flash appears behind of the pursuit direction.

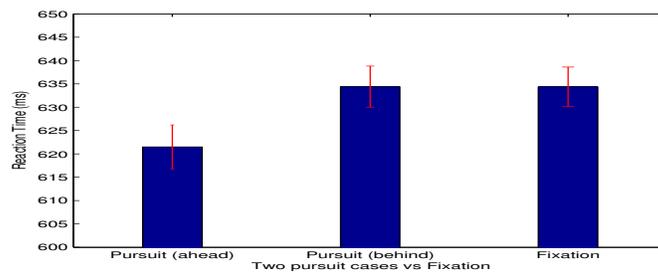


Fig. 9. Comparison of reaction times under the pursuit and fixation conditions.

location of image with high entropy, or were presented at a location in the direction opposite to pursuit, if the eye was moving. For the easy level, enemies were displayed when the eye was fixated at a location of low image entropy, or if the eye was engaged in visual pursuit, the enemies were displayed at a location in the same direction as pursuit.

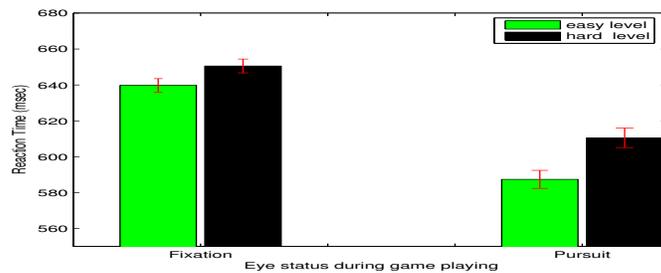
The game was designed as follows. Four types of enemies appeared during games. They were all shooters, either with bullets, bombs, fireballs, or missiles. Three shooters were displayed right from the beginning of the games. They moved horizontally and would shoot while moving. They stopped moving temporarily if they were shot 20 times by the player. The player's score was increased by shooting shooters and was decreased by being shot. In addition to these three shooters, other enemies would appear continuously. The type of enemies and their locations depended on the eye movement information during playing. Bombs would explode shortly after their appearance. To be protected from a bomb blast, the player would need to hide from it. Fireballs would always appear at the right or left bottom corner of the background. They would move horizontally either leftward or rightward, depending on their initial location. To be protected from a fireball, the player needed to jump up from the ground. Scores would be deducted if the player was caught by a bomb blast or a fireball. The missile enemy type was used to trigger eye pursuit in the player. This type of enemy flew horizontally at a speed of 4 deg per second. The player could gain higher scores by pursuing the missile and correctly responding to a number (from 0 to 9) displayed on the missile. The number would appear randomly during the flight of the missile. The player was also allowed to shoot and move horizontally, except while hiding and jumping. The game background was set to images selected from different categories (landscape, city scene, building, animal, plant, etc). Each image background lasted approximately 10 seconds with random numbers of appearance of enemies. A screenshot of the game during play is shown in Figure 10. The size of the image background is the same as that used for the previous experiment, which is 640*480.

The same experimental environment was used in testing the game as in the previous experiment. Five participants (three females, two males) played this game. They were all novices at playing action video games. After the training of playing the games of a mixed level for half an hour, we started recording game data. Each session of the game lasted approximately six minutes. In total, each participant played the game for approximately three hours. Game difficulty levels were alternated randomly for each player without notifying him or her.

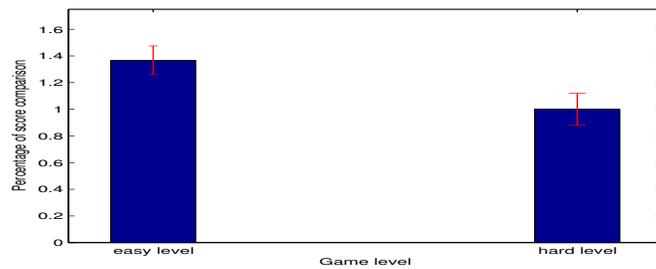
Reaction times and scores were analyzed after the experiment. Figure 11 shows the results. We observed longer reaction times for the hard game and shorter reaction time for the easy game. Statistical significance testing using a Ttest shows significant differences between the reaction times ($p < 0.05$). In addition, the scores for the two levels of games were significantly different. Higher scores were observed for the easy game and lower scores were observed for the hard game. These results indicate that the attentional modeling can be used to alter the game play so as to provide varying difficulty levels.



Fig. 10. One screenshot for the game. The green figures are the three shooters. The blue figure represents players. The red circles show the fixation areas with low and high entropies (low entropy corresponding to easy level, high entropy corresponding to hard level).



(a)



(b)

Fig. 11. Comparison of RT and Scores for hard and easy games. (a) Reaction time comparison for hard and easy levels of the games. For the fixation situation, the light bar represents for easy level (low local entropy) and the dark bar represents for hard level (high local entropy). The same representation for the pursuit situation. (b) Score comparison for hard and easy levels of the games. Mean score for hard level game is taken to be 1.

5. CONCLUSIONS

It is well known that computer games have become a very popular and widespread form of entertainment. Now recent studies have shown that computer games are no longer only for entertainment. Research suggests that games may increase players' attention capacities [4]. Work done by Green and Bavelier found that frequent game players score higher on some attention tasks [6]. And their recent work showed that playing action video games can enhance different aspects of visual processing [7]. Special computer games are also used to help children train their brains to pay attention [26; 1] and seniors to improve their memory and attention. It is becoming promising to apply games to health therapy and training.

Attention plays a critical role during game playing. Better understanding of attention allocation during different tasks will benefit game design. Based on a model of attention allocation, we can make a game harder by placing important game-relevant items in regions with less attention allocation or we can make a game easier by placing important game-relevant items in regions that have more attention allocated. We applied this strategy to an interactive computer game. Our experimental result shows that participants responded significantly differently to items placed at different attention allocation areas. As expected, for eyes fixated in areas with lower local image entropy, reaction to peripheral targets tends to be faster. Attentional benefit was also associated with items appearing ahead of eye pursuit movements.

Both fixation and pursuit eye motion patterns appear during game playing. Because of the different attention allocation strategies in these two conditions, consideration of just one type of eye movement during game design is insufficient. Our test results separating different eye movement types show significant differences of reaction time and scores for each type of eye movement situation.

Eye fixation and pursuit appear not only during game playing but also in our daily lives. Thus, if we want to take advantages of tracking eye movements into applications, such as HCI and entertainment interfaces, it is necessary and beneficial to consider both conditions of eye movements.

The main contribution of this study is its novel consideration of eye movement types: fixation and pursuit in designing video games. The eye movement information is taken to be one of the inputs to the game. Although the same idea can be applied to saccadic eye movements as well, our initial consideration is limited to only fixation and pursuit currently, because the eye spends much less time engaged in saccadic motion than in fixation and pursuit, since they only last a few tens or hundreds of milliseconds.

Ethics Approval Disclaimer The research presented in this paper involved psychophysical experimentation with human participants. Prior to carrying out such experimentation, details of the procedures, techniques, and equipment involved in it were approved by the Ethics Review Committee of the Faculty of Education at McGill University.

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