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On the Gain of Stereoscopic Motion Parallax Reproduction

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ABSTRACT

This paper deals with the reproduction of stereoscopic motion parallax focusing on the ratio of camera movement to head movement ("gain of motion parallax control"). Within the framework of a Human Factors study the experimental task of test subjects was to adjust the gain of motion parallax to perceive a stable and natural stereoscopic image. Earlier experiments at HHI had shown some deviations from theory which says that, in order to perceive an undistorted stereoscopic space and in order to avoid apparent movements, the gain has to be 1. The influence of delay time, which may play a major role especially with satellite links, on the preferred gain was examined as well. No clear dependency of the adjusted gain on delay time could be found. However, the assessed stability of the displayed scene decreased with increasing delay times.

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Depth cues in Human Vision

The human visual system makes use of various kinds of depth cues for distance and size judgements of objects in the visual field: monocular depth cues can be perceived with one eye only whereas binocular ones can only be perceived with both eyes. In natural, non-mediated vision, scene cues that provide information for monocular depth perception (see e.g. Wickens, 1990) include: interposition or occlusion (a closer object hides a more distant one), linear perspective (rectangular surfaces slanting or lines converging in depth, e.g. railway tracks), shadows, highlighting (the reflection of light off a curved surface conveys a sense of its 3-dimensionality), textual gradients (continuous changes in the grain or spatial frequency of texture across the visual field), proximity-luminance covariance (brighter illumination is perceived as being closer), and past experience (if the true size of objects is known, their distance can be estimated more easily). All of these provide depth cues even when seen with one eye only.

In contrast, binocular depth information is based on seeing with two eyes. In stereopsis, the distance between the two eyes results in different images in the two retinas. The spatial difference in the representation of the same spatial coordinates onto corresponding areas of the retinas (disparity) allows of spatial perception.

All depth cues mentioned so far are visible even in a *static* image. Depth cues provided by motion parallax require a *dynamic* view because they lead to relative shifts of objects in the visual field which are dependent on the observer's motions.

On the basis of depth salience and cue conflict studies, Wickens (1990) reported a series of conclusions on the relative importance of the various depth cues listed above. According to this work, stereopsis, motion parallax, and interposition are the most important depth cues with stereopsis dominating all other factors except in case of cue conflict where it can be overridden by motion parallax and interposition information. In Wickens' (1990) study, motion parallax came out as the second most important depth cue.

Motion Parallax

Motion parallax can be defined as a change of view (including relative shifts of objects in the visual field) due to the observer's movements (Sedgwick, 1986). By moving our head, we can see previously hidden or obscured details of the visual field.

Since relative shifts of two objects in the visual field depend on the observer's distance to the objects and on the distance between the two objects, motion parallax provides an important depth cue (it is the only interactive one) that contributes to the naturalness of vision and can reduce artefacts of common stereoscopic representation techniques. It supports distance judgements and size estimations of objects (see e.g. Overbeeke et al. 1988). When moving, observed objects are shifting against each other with different velocities depending on their distance from the fixation point of the observer.

Representing motion parallax in videocommunications and virtual reality applications can be expected to lead to a more natural display because it allows of aspect changes in dependence of the observer's own movements to occur just as in real situations. In addition to leading to more precise distance and size judgements, representation of motion parallax allows the observers to actively explore the visual scene by changing their position.

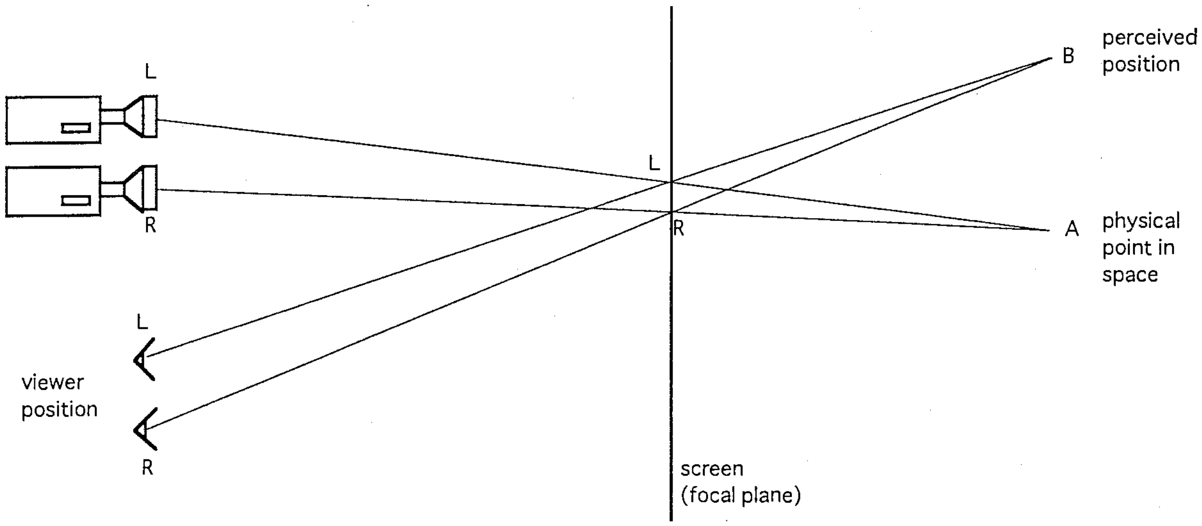

Figure 1: stereoscopic space distortions, if viewing position differs from the centre of perspective

The perceived stereoscopic space is distorted if the viewing position differs from the centre of perspective of the displayed stereo pair (figure 1); these distortions are particularly visible if the observer moves his head. In this case *apparent movements* are visible. Those can only be avoided, if the centre of perspective of the camera coincides at any time with the current viewing position. As a consequence, the system is then capable of providing motion parallax. Camera movement and viewer movement have to correspond with each other. With autostereoscopic multi-view-systems which are now under development (Börner, 1993; Omura et al., 1994), stereoscopic motion parallax reproduction is obvious. Some systems provide a range of discrete perspectives. Other systems track the head position of the observer: this information can easily be used to present images according to the observer's current viewing positions.

EARLIER STUDIES AT HHI

At the Heinrich-Hertz-Institute (HHI) a videoconferencing set-up providing stereoscopic motion parallax reproduction was realized in order to be employed in a Human Factors Experiment (Runde, 1993). Preliminary results of a pre-test using this set-up suggested that the ratio of camera movement to viewer movement ("gain of motion parallax control") under equal shooting and viewing conditions (see below and figure 1) should be smaller than one in order to perceive a stable scene: Test subjects perceived the presented scene as being more natural, when the camera position did not coincide at any time with the current viewing position, as was expected. So, the Human Factors experiment was actually carried out using an experimentally determined gain of motion parallax smaller than the one predicted by the geometrical considerations according to figure 2 (Böcker et al., 1995).

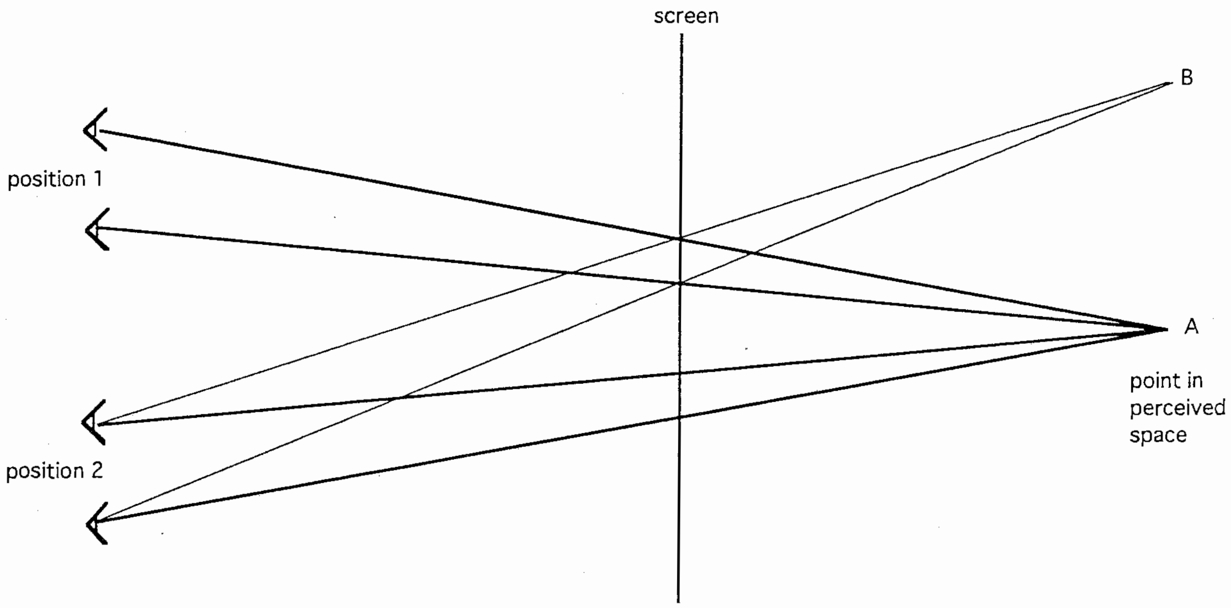

Figure 2: Construction of motion parallax reproduction
With motion parallax reproduction, the object is always perceived at position A, whereas without motion parallax reproduction, the object is perceived as moving from A to B when the observer moves from position 1 to position 2.

THE STUDY AT ATR

It was discussed whether the above mentioned "deviation from theory" observed within the HHI studies was caused by an artefact: One deficiency of the HHI experimental system could have been the delay between head movement and camera movement which was up to 180 ms, even though Satoh et al. (1991) stated that a delay up to 180 ms is permissible with horizontal head movements. The delay was caused by the head detection system and the inertia of the mechanically tracked cameras. So it was decided to carry out experiments aiming at examining the dependency of the preferred gain on delay time with stereoscopic motion parallax reproduction (for monoscopic motion parallax reproduction see Hoshino et al., 1991). These experiments were conducted by an HHI visiting scientist at ATR.

It was expected that test subjects would prefer a gain of 1 under the condition of undetectable delay times and that the preferred gain would decrease with increasing delay times for most observers to reduce the disturbing effects of delays.

TECHNICAL SET-UP

The development of the technical set-up mainly consisted of three work packages: set-up control, scene capturing, and image representation.

Set-up Control

The set-up was controlled by a PC 486 DX 66-2. Analog signals from an ultrasonic position detection system and a slide control were converted into digital data. Two frame buffers with 64 RGB- or 3 x 64 grayscale-frames each were provided. In order to avoid flipping (see Pastoor et al., 1989) and to provide an adequate movement range of the observer, grayscale images were chosen for the experiments. A menu-driven software with a wealth of options (see Appendix) was developed in C++.

Scene Capturing

A natural reproduction of motion parallax ought to give the impression of looking through a window. Three different scenes were captured using a 3-Chip CCD camera. To realize an undistorted stereoscopic image representation shooting and viewing conditions were the same. The viewing distance and the shooting distance to the plane of convergence was 2.7 m in all experiments. The stereo base (i.e. the distance between the two camera lenses) when capturing the images was 65 mm (= average interocular distance). Parallel camera axes were chosen to avoid keystone distortions. The camera shift between two takes was 2 mm to avoid flipping (see Pastoor et al., 1989). Image positions were adapted electronically, so that the zero parallax plane, which should be perceived as the window plane, was represented without motion. (See figure 2: Image points for the left and right eye coincide, if the point in perceived space coincides with the screen plane. The screen positions of these points have to remain fixed even when the viewer moves.) A frame buffer providing 189 grayscale frames for each of the stereopairs was used.

Image Representation

Figure 3 shows the experimental set-up for image representation. The test subject sat in front of a rear projection screen wearing a sensor of an ultra-sonic head position detecting system. The separation of the images for the left and right eyes was achieved by using linear polarization filters. The horizontal viewing angle was 12.5° and the viewing distance was 2.7 m. The two objects of the captured scenes were represented with screen parallaxes of about 10 and 17 mm respectively.

The stereopairs were presented according to the head position of the observer, so that he saw different views of the scene when moving his head laterally. Using a slide control, the ratio of (pre-recorded) camera movement to head movement could be adjusted by the observer. The images were projected by two NTSC-LC-projectors which were equipped with orthogonal linear polarizing filters.

Delay times could be adjusted field-wise (i.e. every 16.7 ms) by the experimenter. The shortest achievable delay time was 33 ms (i.e.: two fields = one frame).

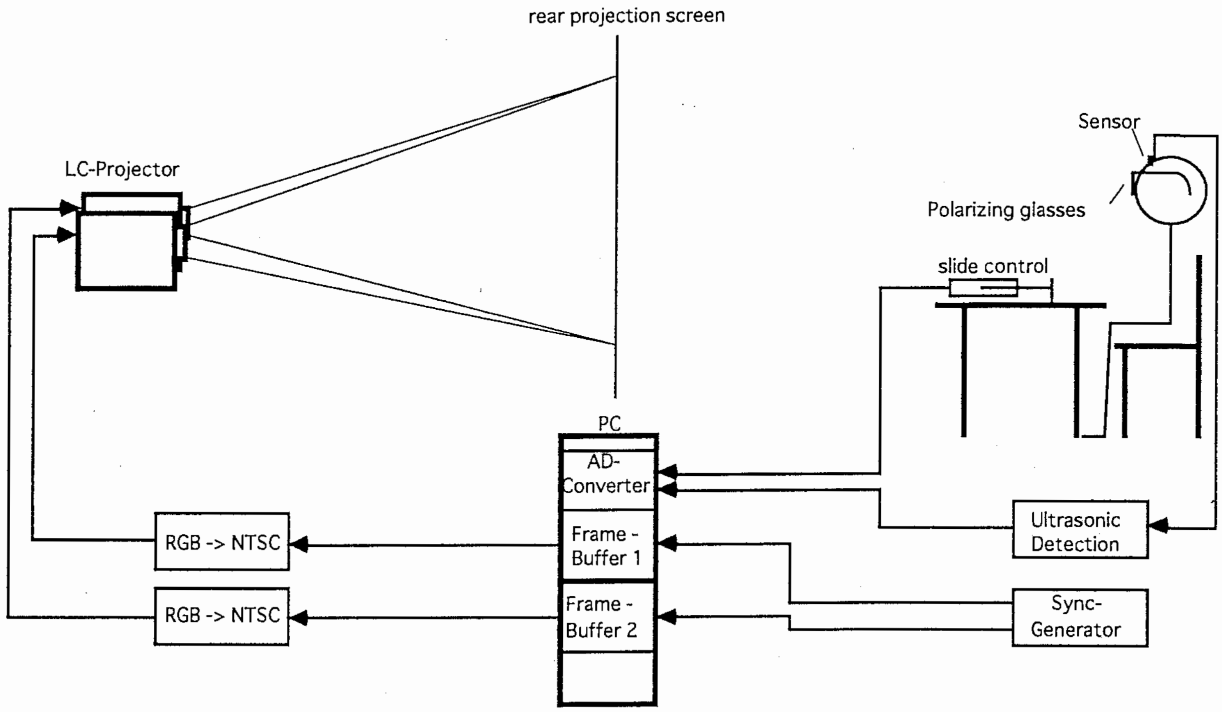

Figure 3: experimental set-up

EXPERIMENTAL METHOD

Six slightly different experiments were carried out in order to examine the effects of gain of motion parallax, delay time, and characteristics of the scene (e.g. occlusions) on the perception of a natural and stable looking scene. All experiments realized motion parallax reproduction with horizontal frontoparallel head movements.

Five test subjects (members of the ATR staff) who where familiar with stereoscopic image representation took part in the first four experiments. The test subjects had to adjust the gain they would prefer and to assess the quality of motion parallax control:

Experiment 1: A flat white rectangle (5.5 cm x 4.5 cm in size) was displayed with three different screen parallaxes (p) to be perceived in front of (p = - 28 mm), directly on (p = 0 mm) and behind the screen plane (p = + 28 mm). No additional depth cue was provided.

Experiment 2: Scene 1: A captured grayscale scene with only one object (a book) and an unstructured white background was provided. The whole scene was perceived as being behind the screen plane.

Experiment 3: <u>Scene 2</u>: A captured grayscale scene with two objects (a book and a tin of cylindrical shape further away) and an unstructured white background was provided. The whole scene was perceived as being behind the screen plane. There were no overlapping or occlusions between the two objects.

Experiment 4: <u>Scene 3</u>: A captured grayscale scene with two objects (a book and a tin of cylindrical shape further away) and an unstructured white background was provided. The whole scene was perceived as being behind the screen plane. The second object was always partly occluded by the first object.

The following eleven different delay times were chosen, the sequence of which was alternated in the experiments:

- 33 ms
- 50 ms
- 67 ms
- 83 ms
- 100 ms
- 133 ms
- 167 ms
- 200 ms
- 300 ms
- 400 ms
- 500 ms.

Earlier experiments of Satoh et al. (1991) and the experiments at HHI led to the decision of concentrating on delay times lower than 200 ms. But in order to cover satellite links, greater delay times up to 500 ms were examined as well (transmission time of one way geostationary satellite link is in the order of 210 ms (without decoder delay time)).

In all experiments test subjects were asked to move their head frontoparallel to the projection screen. Using a slide control (stroke: 10 cm) the test subject could adjust the gain of motion parallax reproduction.
In experiment 1 the range of gain values (representing the ratio of head movement to a virtual camera movement) was -1.56 ... +1.40.
In experiments 2 - 4 the range of adjustable values was 0.00 ... 1.27 with 0.00 = no motion parallax reproduction, and 1.00 = calculated gain.

In experiment 1 the rectangle was presented with different screen parallaxes (depths) and different delay times.
Test subjects were asked to adjust the gain, so that they perceive a stable, non-moving object in space while moving their head laterally.
After each adjustment they were asked to judge the quality of their personal adjustment.

	5	4	3	2	1
5-point-rating-scale:	excellent	good	fair	poor	bad

In the first part of experiments 2 - 4 the scenes were presented with different delay times.
Test subjects were asked to adjust the gain of motion parallax in order to perceive a stable scene ("like looking through a real window") when moving their head.
After each adjustment they were asked to judge the quality of their own adjustment (5-point-rating-scale: see above) and to evaluate their confidence in the adjustment.

	5	4	3	2	1
5-point-rating-scale:	totally sure	...	...	...	totally unsure

In the second part of these three experiments, they had to evaluate the quality of motion parallax reproduction with three pre-adjusted gains (1.00, 0.75, 0.50) and the eleven different delay times mentioned above.

The first four experiments were followed by another two experiments. Again, the task was to adjust the preferred gain under the conditions of eleven different delay times and different scenes. However, in contrast to the first four experiments the test subjects were not familiar with stereoscopic image presentation. Twelve subjects participated in the two experiments. Ten of them were Japanese (students), two were German.

Experiment 5: <u>Scene 2</u>: A captured grayscale scene with two objects (a book and a tin of cylindrical shape further away) and an unstructured white background was provided. The whole scene was perceived as being behind the screen plane. There was no overlap or occlusion of the two objects.

Experiment 6: <u>Scene 3</u>: A captured grayscale scene with two objects (a book and a tin of cylindrical shape further away) and an unstructured white background was provided. The whole scene was perceived as being behind the screen plane. The second object was always partly hidden by the first object.

The sequence in which the scenes of Experiment 5 and Experiment 6 were allocated to the subjects was alternated. The first experiment began with a trying-out phase, so that the test subject had the opportunity to get familiar with the experimental procedure:

- Two real objects are shown, to remind the test subject, what motion parallax is about.
- Watching the presented scene while moving the head laterally with different pre-adjusted gains of motion parallax with a delay time of 33 ms.
- Explanation of the quality rating scale: The test subjects should evaluate the quality of the stability of the presented scene while moving their head laterally. They should compare it with the impression they would have when looking at this particular scene through a real window.

Each experiment was divided into two parts:

In Part 1 they were asked to evaluate the quality (5-point-rating-scale) of the image representation while moving their head laterally with 13 pre-adjusted gains (from 0.0 to 1.2 in 0.1 steps, in a random order) with a constant delay time of 33 ms.

In Part 2 they were asked to adjust their preferred gain (as best as possible) within a range of adjustable values from 0.00 to 1.27 and to evaluate the quality (5-point-rating-scale: see above) of this scene presentation while moving their head laterally with eleven different delay times (from 33 ms to 500 ms, see above).

Table 1 outlines the main features of the experiments mentioned above.

experiment	scene	screen parallax	delay time [ms]	gain of motion parallax	evaluation
1 (5 test subjects)	computer generated symbol: flat rectangle	-28 mm 0 mm +28 mm	33, 50, 67, 83, 100, 133, 167, 200, 300, 400, 500	to adjust	quality
2 (5 test subjects)	captured grayscale image: one object	(10 mm)*	33, 50, 67, 83, 100, 133, 167, 200, 300, 400, 500	to adjust	quality, certainty
				0.5, 0.75, 1.0	quality
3 (5 test subjects)	captured grayscale image: two objects, no occlusions	(10 mm, 17 mm)*	33, 50, 67, 83, 100, 133, 167, 200, 300, 400, 500	to adjust	quality, certainty
				0.5, 0.75, 1.0	quality
4 (5 test subjects)	captured grayscale image, two objects with occlusions	(10 mm, 17 mm)*	33, 50, 67, 83, 100, 133, 167, 200, 300, 400, 500	to adjust	quality, certainty
				0.5, 0.75, 1.0	quality
5 (12 test subjects)	captured grayscale image: two objects, no occlusions	(10 mm, 17 mm)*	33	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2	quality
			33, 50, 67, 83, 100, 133, 167, 200, 300, 400, 500	to adjust	quality
6 (12 test subjects)	captured grayscale image: two objects with occlusions	(10 mm, 17 mm)*	33	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2	quality
			33, 50, 67, 83, 100, 133, 167, 200, 300, 400, 500	to adjust	quality

* no parameter of variation: the mentioned screen parallaxes are those of the objects of the scene.

Table 1: experimental design

RESULTS

General Results

The ratio of camera movement to head movement (gain) for a realistic image representation with motion parallax reproduction differs from person to person from nearly the calculated one (i.e. 1, see above) down to only 10 % of it or even less. No common gain of motion parallax that satisfies the needs of all subjects could be found.

No clear dependency of the gain on the delay time could be found. Only few subjects preferred a smaller gain with increasing delay times.

In most cases, the quality ratings decrease with increasing delay times. Trying to look for a threshold for each subject leads to values between 83 ms and 300 ms. On average this threshold is about 170 ms.

The results in detail:

Experiment 1

a) screen parallax = -28 mm

One subject did not compensate for apparent movements but increased them.

The other four test subjects adjusted gains with short delay times between 0.09 and 0.77; with greater delay times the preferred gain decreased in most cases (see figure 4 in the appendix).

On average, the quality of the adjustment got good ratings up to 83 ms (see figure 5 in the appendix).

b) screen parallax = +28 mm

On average, the adjusted gain was between 0.33 and 0.60 up to 200 ms delay time. With greater delay times than 200 ms, the preferred gain decreased. The different gains adjusted by the test subjects were varying to a greater extend above 167 ms (see figure 6 in the appendix).

On average, the quality of the adjustment got worse with longer delay times than 100 ms (see figure 7 in the appendix). The quality was rated worse than with a screen parallax of -28 mm.

Experiment 2

The average of the adjusted gain of motion parallax up to 133 ms is between 0.18 and 0.33 (see figure 8 in the appendix).

On average, the quality of the adjusted gain gets better ratings with delay times up to 167 ms (see figure 9 in the appendix) and their confidence in the adjustment decreased with delay times greater than 133 ms.

On average, the quality of the pre-adjusted gain 0.50 was judged with 3.11, the quality of 0.75 was 2.45 and the one of 1.00 was 2.07. The quality of the pre-adjusted gains got better ratings with delay times up to 167 ms.

Experiment 3

One test subject preferred significantly higher gains than the others (around 1). No one of the other test subjects adjusted higher gains than 0.50.

The average of the adjusted gain up to 133 ms was between 0.35 and 0.47 (see figure 10 in the appendix).

On average, the quality of the adjusted gain (see figure 11 in the appendix) and their confidence in the adjustment got better ratings with delay times up to 167 ms.

On average, the quality of the pre-adjusted gain 0.50 was judged with 2.95, the quality of 0.75 was 2.51 and the one of 1.00 was 2.31. The quality of the pre-adjusted gains got better ratings with delay times up to 167 ms.

Experiment 4

One test subject preferred significantly higher gains than the others (around 1). No one of the other test subjects adjusted higher gains than 0.50.

The average of the adjusted gain up to 133 ms was between 0.39 and 0.48 (see figure 12 in the appendix).

On average, the quality of the adjusted gain got better ratings with delay times up to 100 ms (see figure 13 in the appendix) and their confidence in the adjustment decreased with delay times greater than 83 ms.

On average, the quality of the pre-adjusted gain 0.50 was judged with 3.02, the quality of the gain 0.75 was 2.49 and the one of 1.00 was 2.25. The quality of the pre-adjusted gains got better ratings with delay times up to 167 ms.

Experiment 5 and 6

The gain of motion parallax for a realistic image representation differed from person to person from the calculated one down to only 10 % of it or even less (see figure 14 and figure 15 in the appendix). No common gain that satisfies the needs of all subjects could be found. The preferred gain did not depend on the delay time (see figure 16 and figure 17 in the appendix).

But the perceived quality did. The quality ratings decreased with increasing delay times in most cases. Trying to look for a threshold for each subject leads to values between 83 ms and 300 ms. On average this threshold was about 170 ms. It was more distinct with the scene of experiment 5 than with the scene of experiment 6 (see figure 18 and figure 19 in the appendix).

No significant difference could be found between the two scenes concerning the gain adjustments (average adjustment with experiment 5 is 0.62; with experiment 6 it is 0.55) and the average quality ratings (the mean quality rating of all subjects and all delay times is 3.65 with experiment 5 and 3.72 with experiment 6).

In another part of these experiments, subjects were asked to judge pre-adjusted gains. In most cases a certain range of good gains was found by the subjects. These areas of "good gains" also differed from person to person.

DISCUSSION

The experiments showed that the assumptions that all viewers would prefer a "geometrically correct" motion parallax reproduction with short delay times and that the preferred gain decreases with increasing delay times were wrong: The preferred gain of motion parallax did not clearly depend on delay times. This may be due to disturbances of visual perception caused by some of the major differences between natural vision and observation of stereoscopic images (e.g. separation of accommodation and convergence). Another unexpected result were the great inter-individual differences between subjects in terms of the preferred gain of motion parallax. Because these issues call for further research, a work package within a new HHI project is dealing with the study of motion parallax control.

As a preliminary conclusion one can state that the delay time of a stereoscopic motion parallax reproduction should not exceed 83 ms in order to achieve a good image representation for all observers.

Further research is necessary to find a technical solution that satisfies the needs of all observers with only one common gain of motion parallax. Otherwise, the gain would have to be adjustable to the individually preferred one in order to provide a natural image representation for each user; a solution that would not be very convincing from a Human Factors point of view.

Another problem may arise with different gains of motion parallax in videocommunication systems: Motion parallax reproduction with a gain of 1 provides eye-contact between remote conferees. Using different gains would lead to a loss of horizontal eye-contact. It should be possible to design a system that suits most applications so that the emerging angles between the camera position and the position of the displayed interlocutor are acceptable by the user (i.e. less than 8°, see Hopf et al., 1994).

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APPENDIX

Software options

The menu-driven software for controlling the set-up provides the following options:

- use of the frame buffers for color or grayscale images
- capturing of single images or a sequence of images
- saving of the buffer content to harddisk
- loading images from harddisk into the frame buffer
- presentation of the buffer content as single images or as a sequence of images with adjustable presentation time (for test purpose)
- generation of test pattern (color bars, hatch pattern) for adjustment purposes
- shifting of the image content within the frame buffer (pixel-wise) to compensate for camera shifts between two takes employing parallel camera axes
- adjustment of image width to adapt the image sides for the left and right eye
- motion parallax reproduction using the content of the frame buffers
    - with different delay times
    - with different gains adjusted by the experimenter
    - with different gains adjusted by the observer
- motion parallax reproduction using a computer-generated symbol
    - with different delay times
    - with different screen parallaxes
    - with different gains adjusted by the observer.

Figures

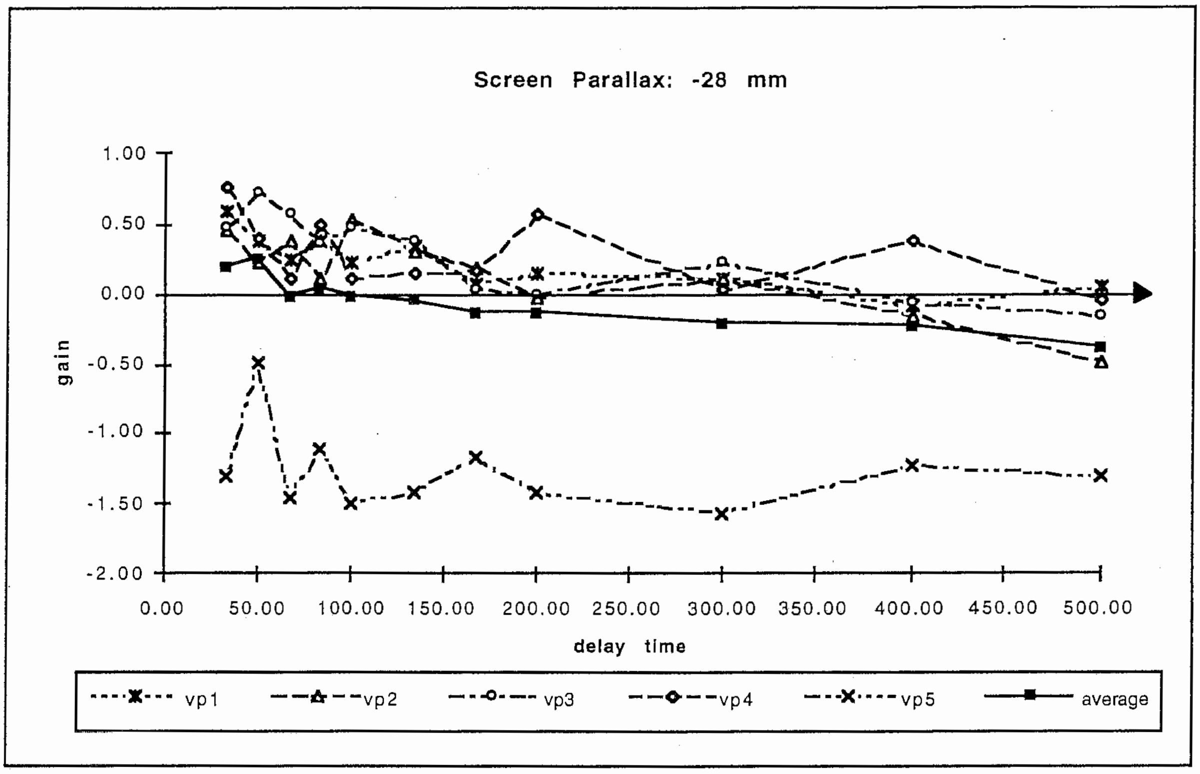

Figure 4: Experiment 1, screen parallax = - 28 mm, adjustment of gains

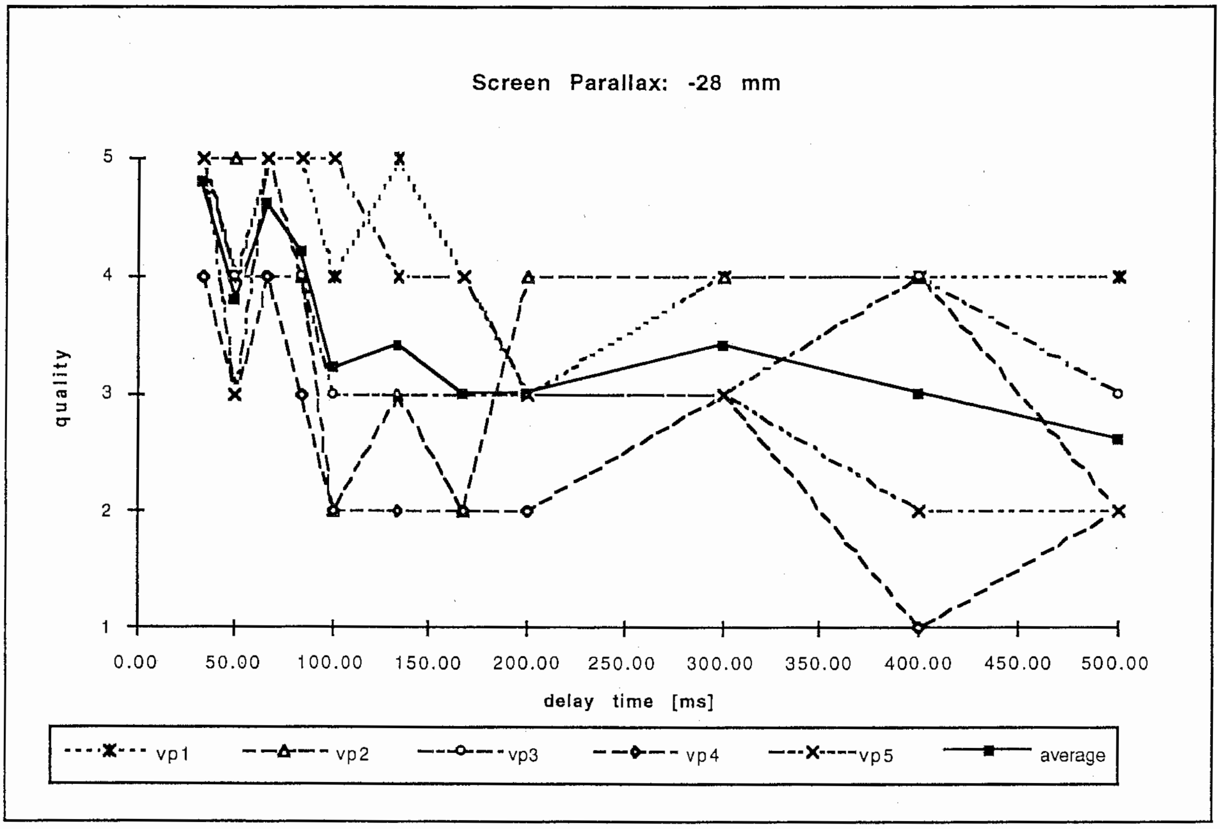

Figure 5: Experiment 1, screen parallax = - 28 mm, quality ratings (5 = excellent, 1 = bad)

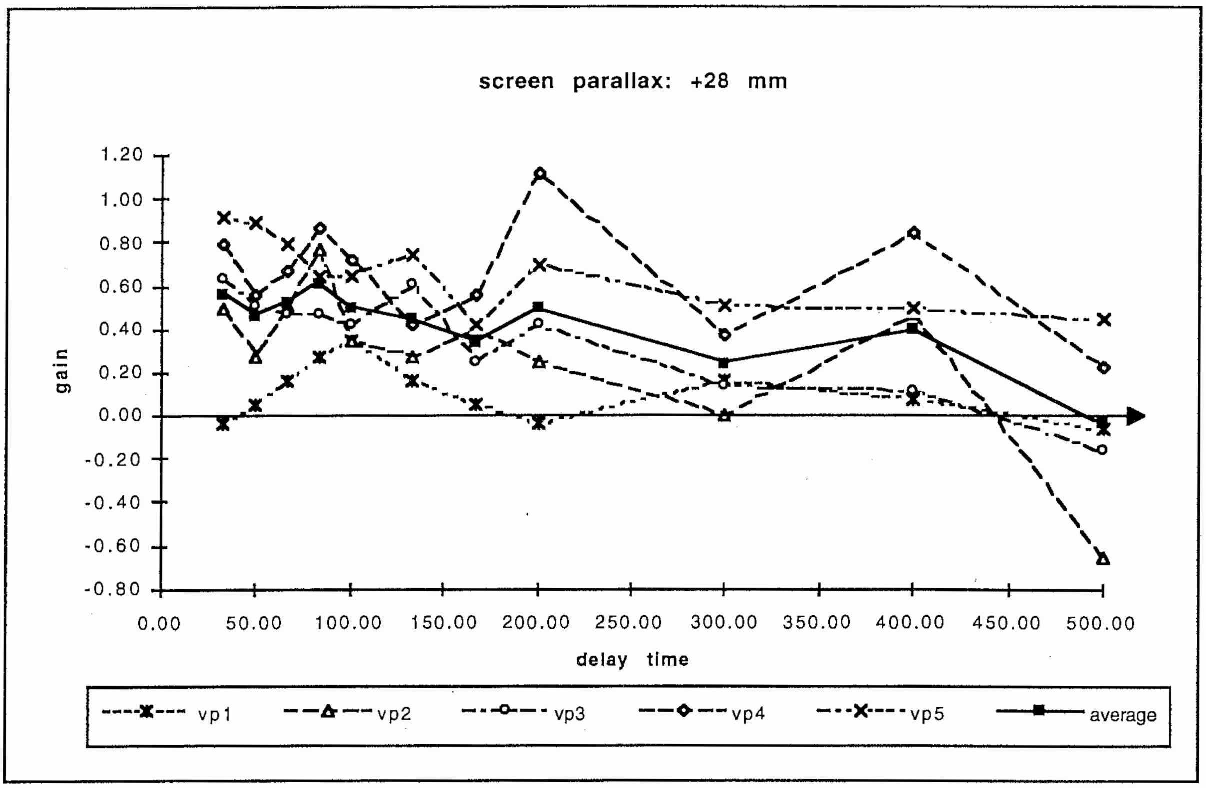

Figure 6: Experiment 1, screen parallax = + 28 mm, adjustment of gains

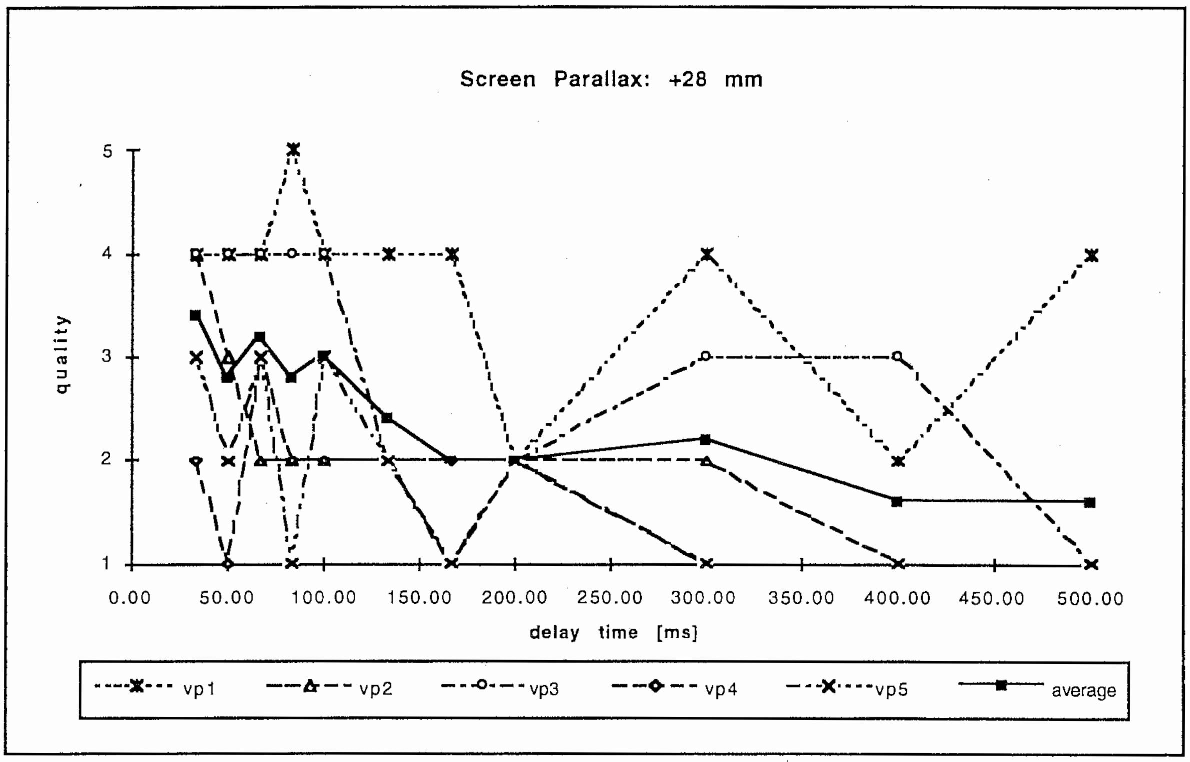

Figure 7: Experiment 1, screen parallax = + 28 mm, quality ratings (5 = excellent, 1 = bad)

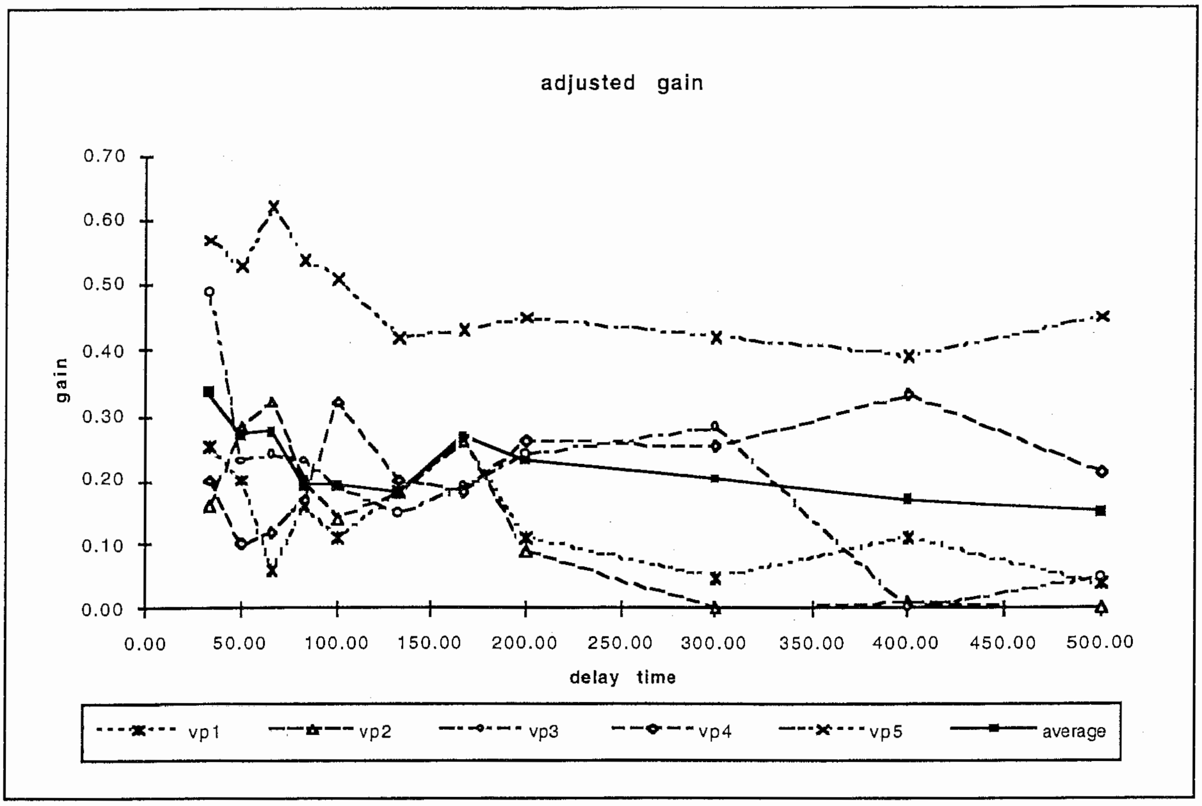

Figure 8: Experiment 2, adjustment of gain

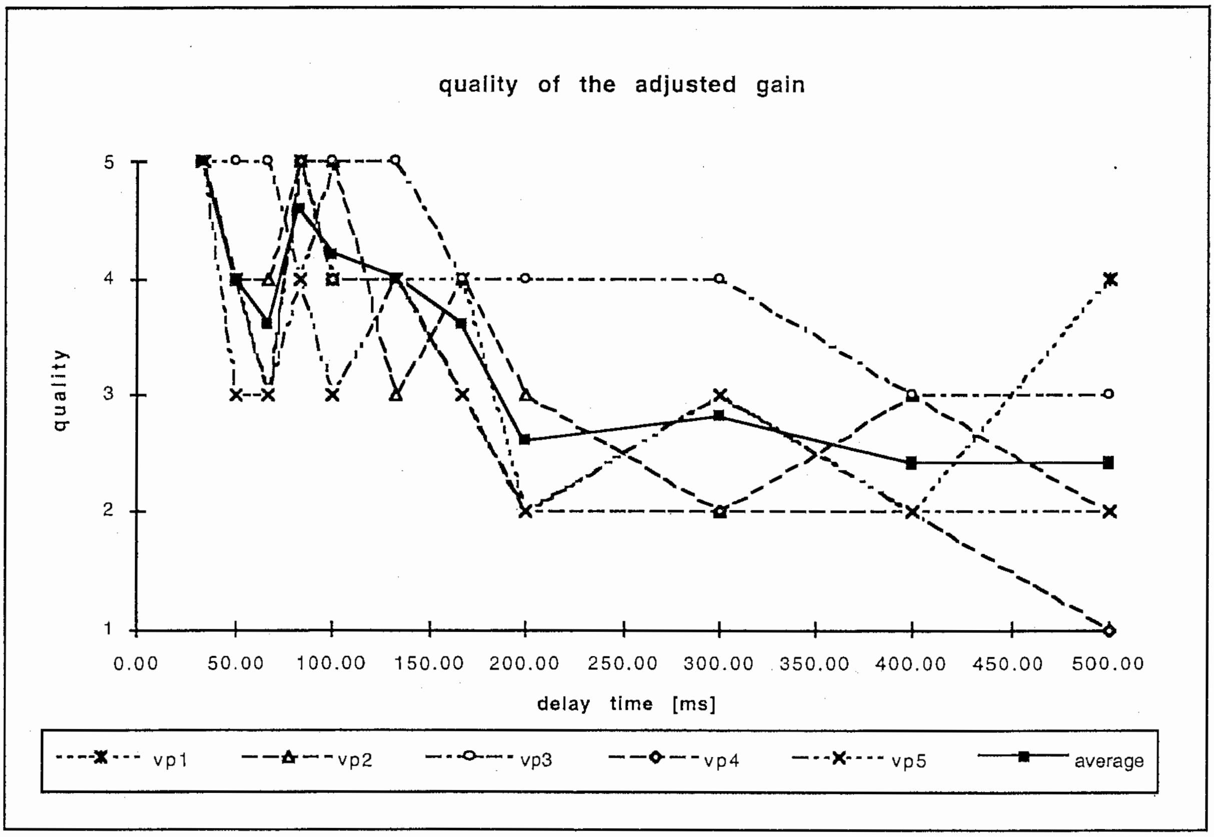

Figure 9: Experiment 2, quality ratings (5 = excellent, 1 = bad)

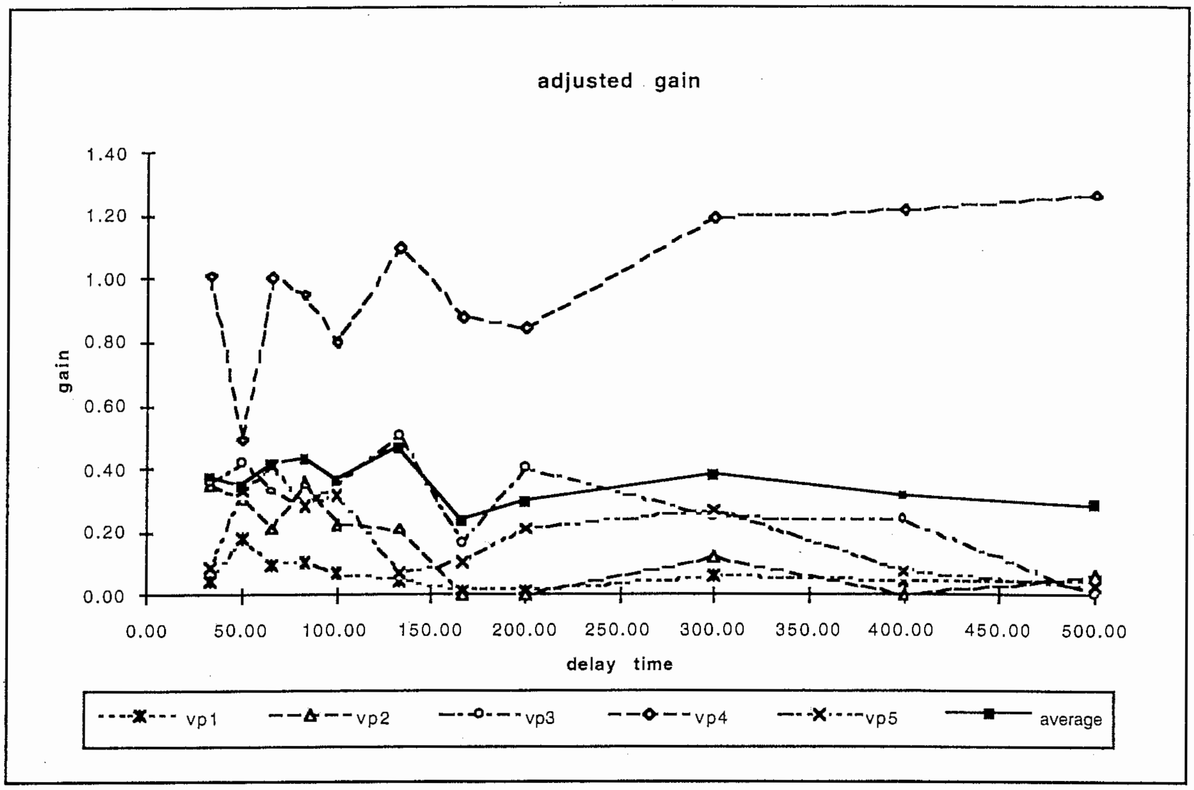

Figure 10: Experiment 3, adjustment of gain

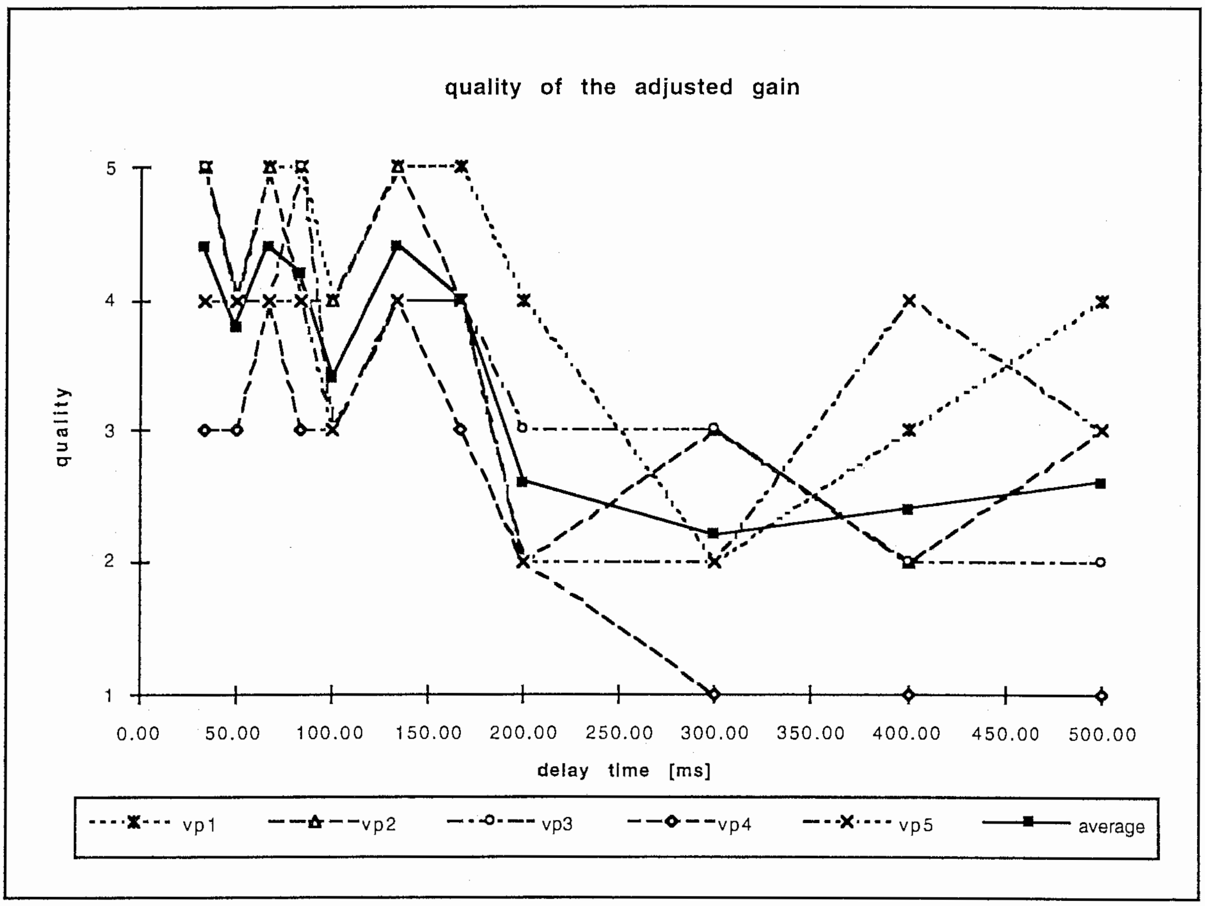

Figure 11: Experiment 3, quality ratings (5 = excellent, 1 = bad)

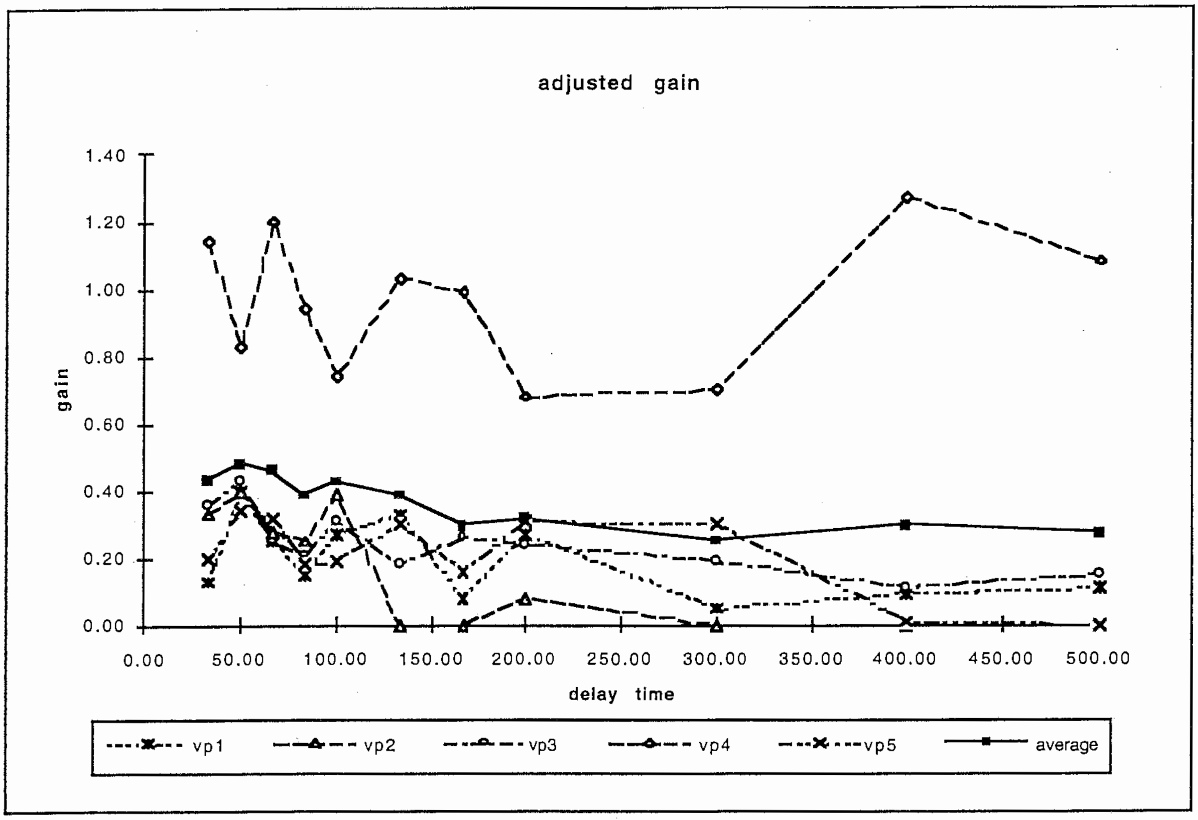

Figure 12: Experiment 4, adjustment of gain

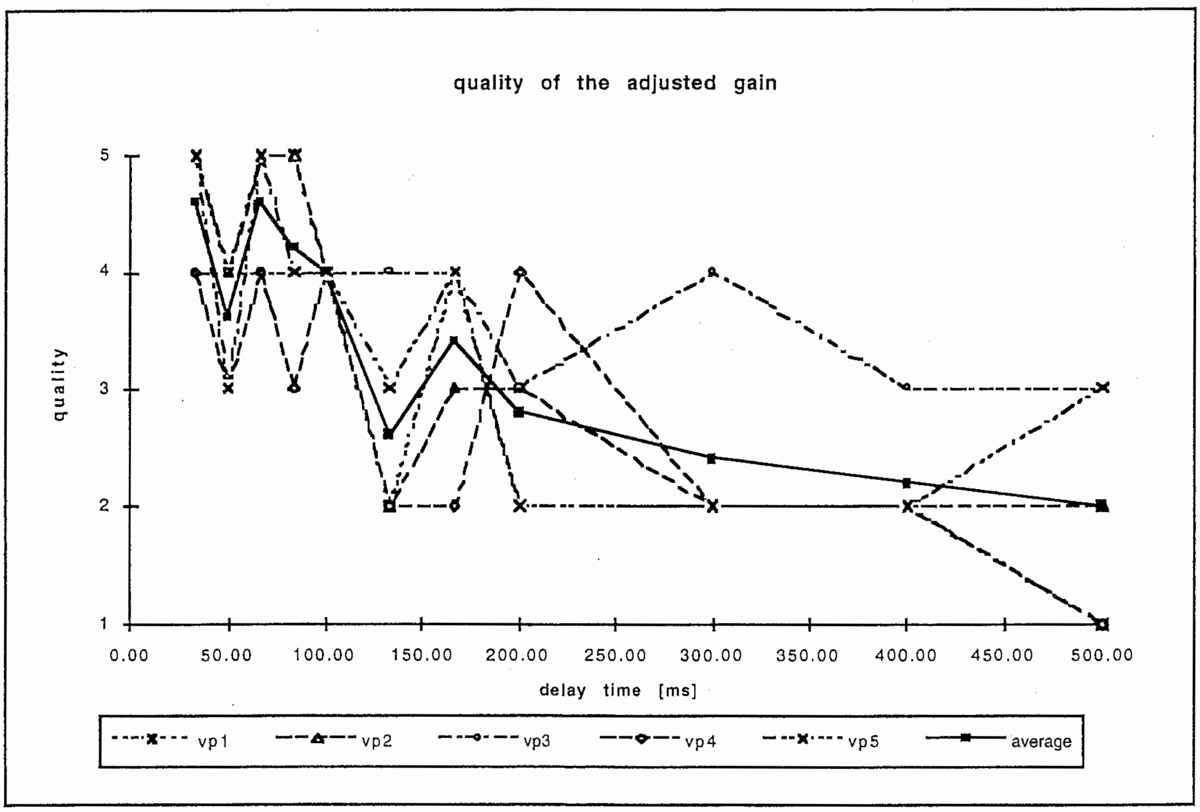

Figure 13: Experiment 4, quality ratings on average (5 = excellent, 1 = bad)

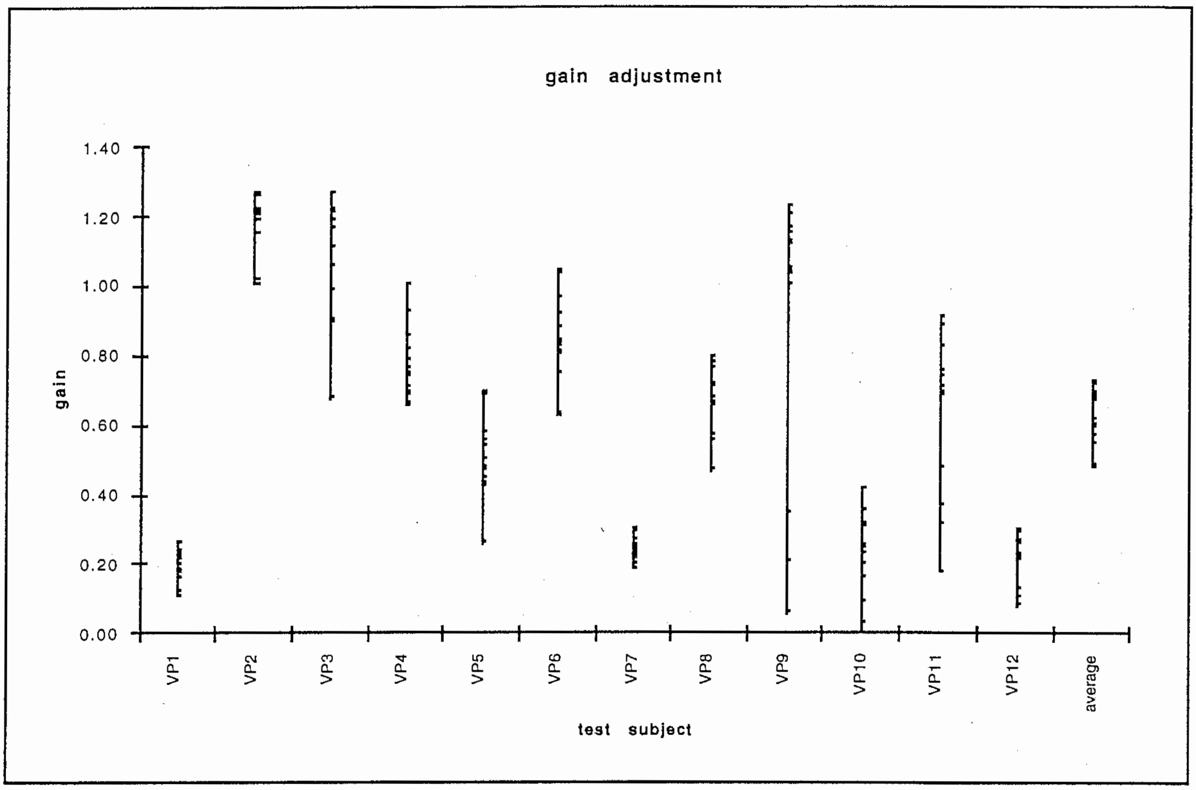

figure 14: Experiment 5, adjustment of gain

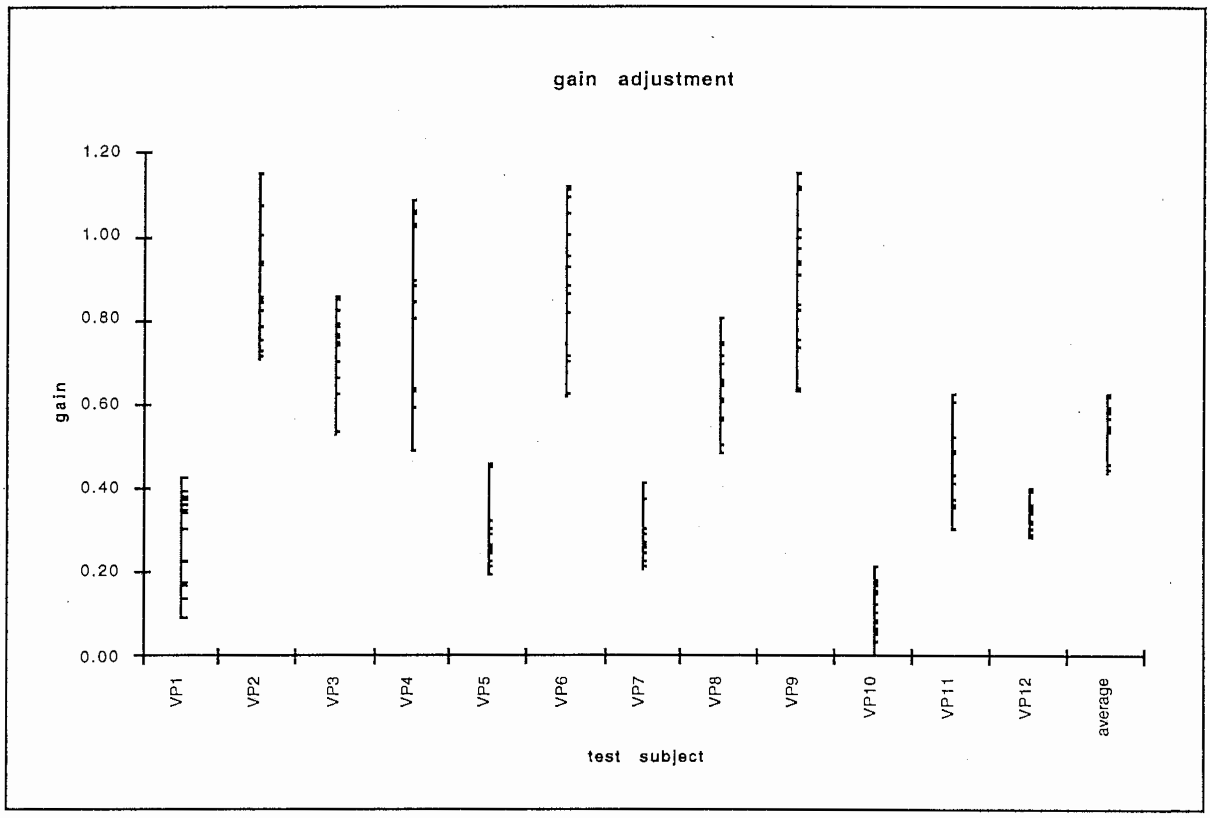

figure 15: Experiment 6, adjustment of gain

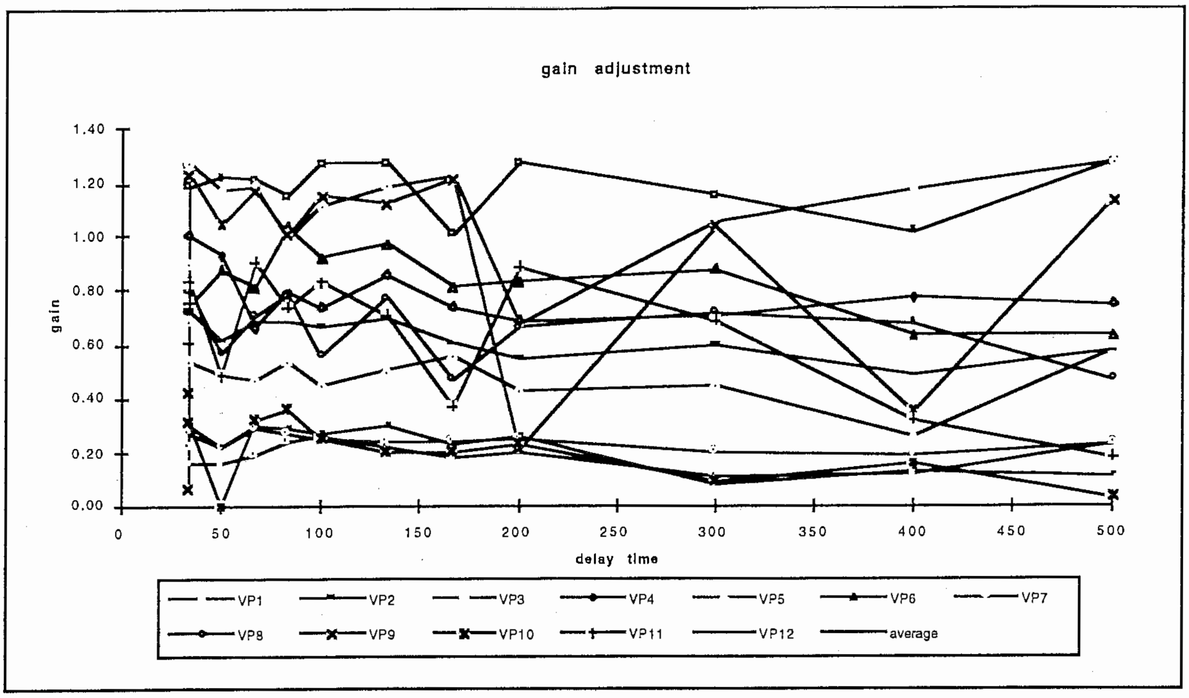

figure 16: Experiment 5; adjustment of gain

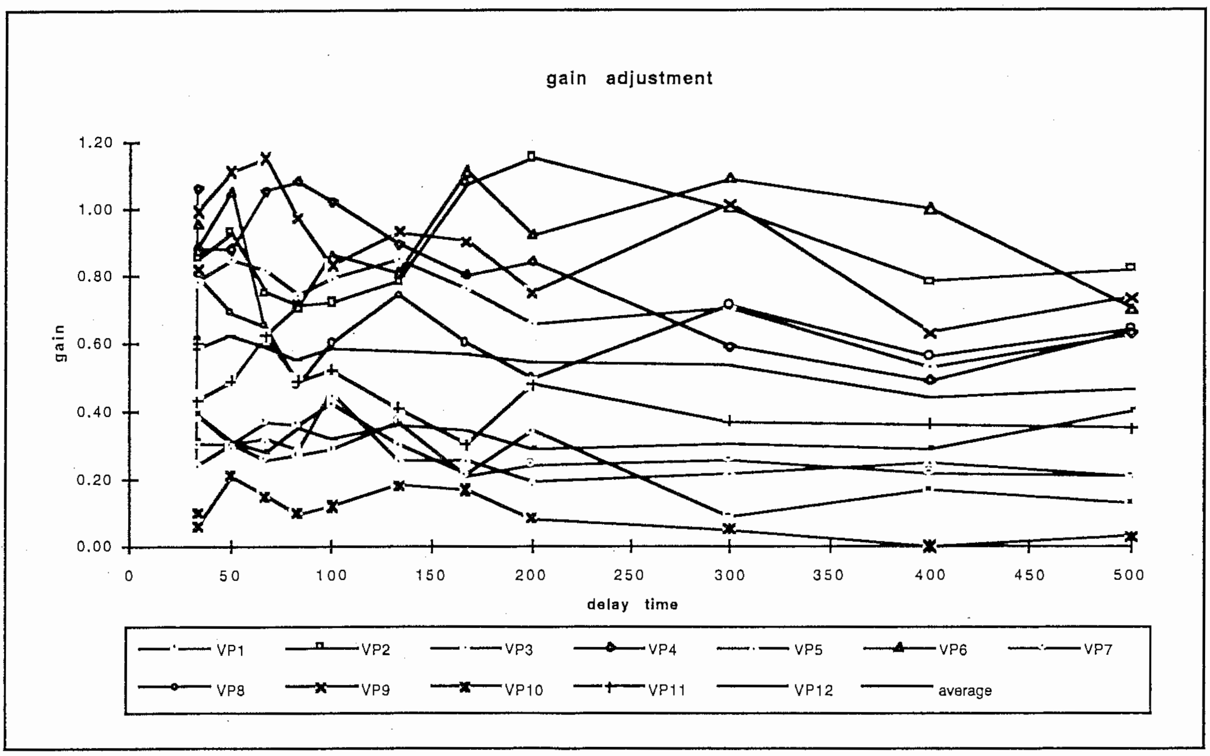

figure 17: Experiment 6; adjustment of gain

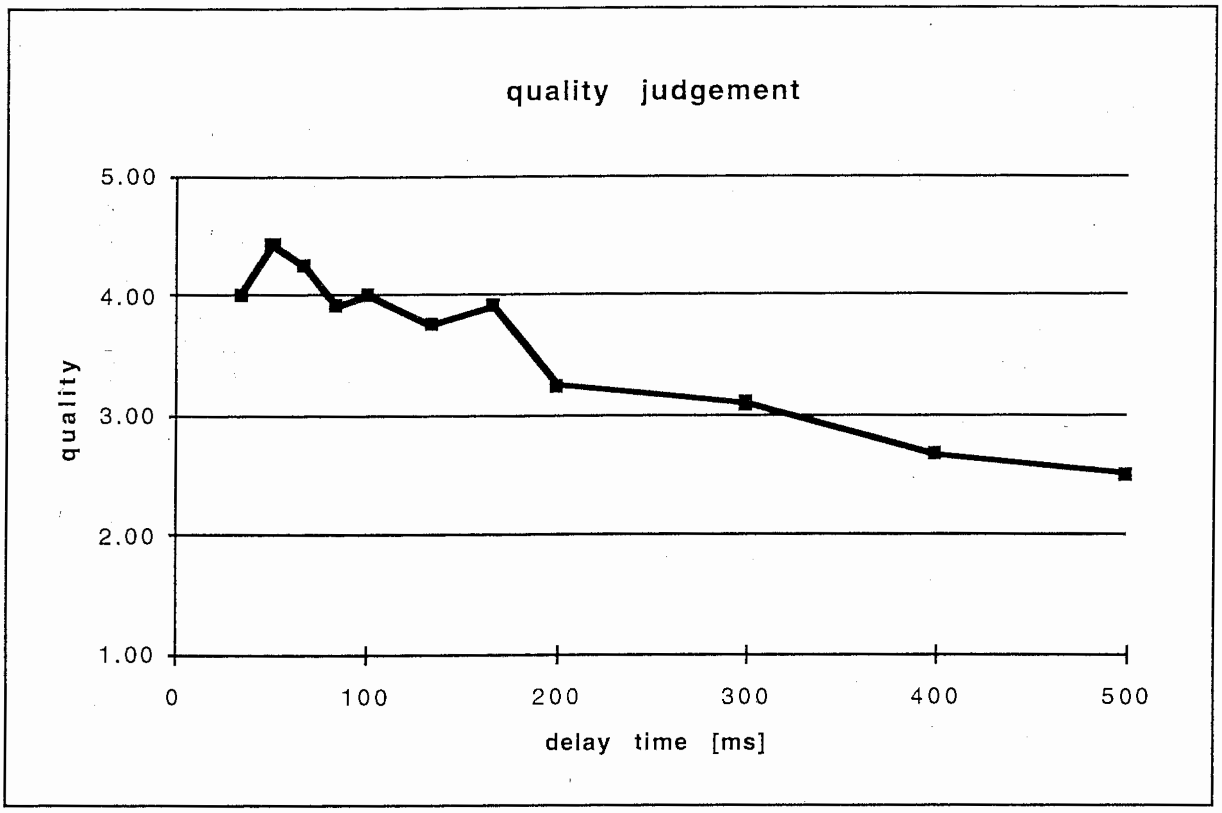

Figure 18: Experiment 5, quality ratings on average (5 = excellent, 1 = bad)

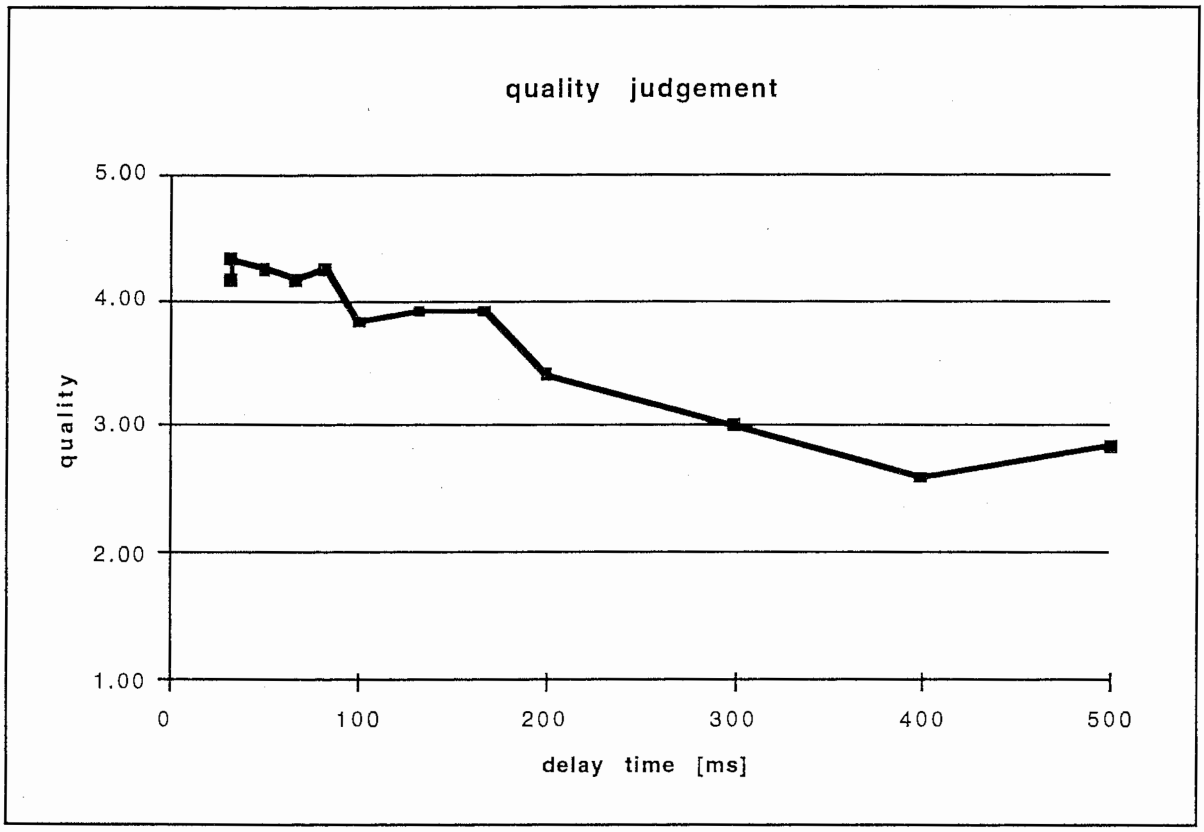

Figure 19: Experiment 6, quality ratings on average (5 = excellent, 1 = bad)