NASA-CR-200623

Annual Progress Report

Period Covered: 5/1/95-4/30/96

NASA Cooperative Research Agreement
NCC2-542

Psychophysical Evaluation of Three-Dimensional Auditory Displays

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Madison, WI 53705

Introduction

This report describes the progress made during the second year of a three-year Cooperative Research Agreement (CRA NCC2-542). The CRA proposed a program of applied psychophysical research designed to determine the requirements and limitations of three-dimensional (3-D) auditory display systems. These displays present synthesized stimuli to a pilot or virtual workstation operator that evoke auditory images at predetermined positions in space. The images can be either stationary or moving. In previous years, we completed a number of studies that provided data on listeners' abilities to localize stationary sound sources with 3-D displays. The current focus is on the use of 3-D displays in "natural" listening conditions, which include listeners' head movements, moving sources, multiple sources and "echoic" sources. The results of our research on one of these topics, the localization of multiple sources, was reported in the most recent Semi-Annual Progress Report (Appendix A). That same progress report described work on two related topics, the influence of a listener's a-priori knowledge of source characteristics and the discriminability of real and virtual sources. In the period since the last Progress Report we have conducted several new studies to evaluate the effectiveness of a new and simpler method for measuring the HRTFs that are used to synthesize virtual sources and have expanded our studies of multiple sources. The results of this research are described below.

Detailed Progress Report

Evaluation of simplified HRTF measurement strategies. Virtual auditory targets are localized at their intended positions only if the digital filters used to synthesize them closely match the listener's own HRTFs. An imperfect match between synthesis filters and the listener's HRTFs can occur either because the HRTF measurements are bad or because the measurements used for the synthesis were from a listener with very different HRTFs. With a poor match, listeners make localization errors, the most common of which are front-back confusions. Thus, the fidelity of a virtual auditory display may depend on the use of individually measured HRTFs. Unfortunately, measuring HRTFs is typically a difficult and time-consuming process. In the previous Annual Progress Report (5/1/94-4/30/95) we described preliminary experiments designed to evaluate a simple technique for measuring HRTFs, based on a commercial device, "Snapshot" (Crystal River Engineering). The main simplification offered by Snapshot involves HRTF measurement at the entrance to the ear canal, with a microphone that seals the canal.

Two kinds of experiments were reported previously. The first involved mathematical analysis of HRTFs measured both with the new system and with the conventional probe microphone system. The second consisted of a series of localization experiments in which listeners indicated the apparent positions of virtual sources synthesized from both new and conventional HRTF measurements. The results of all the experiments were encouraging. The mathematical analysis, which was based on Multidimensional Scaling of differences among sets of HRTFs showed that the differences between HRTFs measured with the new and conventional systems was no greater than repeated measurements from a given listener for each system alone. The localization experiments showed that the patterns of apparent position judgments were nearly the same for virtual sources synthesized from both newly and conventionally measured HRTFs.

A third experiment was completed during the current funding period. This experiment addressed the fact that apparent position judgments may not capture subtle differences between HRTFs that may be important for synthesizing veridical virtual sources. Such differences may, for example, lead to differences in image diffuseness or size. While the multidimensional scaling analyses provide a compact and robust expression of physical differences between HRTFs, the connections between those physical differences and the resulting perceptual differences are uncertain. We conducted a discrimination experiment to quantify those differences. In an abx paradigm listeners attempted to discriminate between noise signals filtered through various pairs of HRTFs.

From the large initial database of HRTFs 12 representative sets (6 listeners, two microphone systems) were selected for further testing. Each listener in the discrimination experiment was tested with all possible pairings of HRTF sets. For a given 200-trial block one of the 66 pairs was chosen, and 20 stimuli were synthesized using these two HRTF sets at each of 10 virtual source positions (all on left side). On each trial listeners discriminated (monaurally, left ear) between two noise bursts that had been filtered with HRTFs from the same position but from different listeners and/or microphone systems. Correct answer feedback was provided after each trial. A 2-D projection of the 3-D scaling analysis of the discriminability indices (d') obtained from a typical listener are plotted in Fig. 1. Upper case letters refer to data from new HRTF measurements and lower case refers to data from conventional HRTF measurements. The goodness of fit between this scaling solution (85% variance accounted for) and the scaling solutions based on the physical difference measures (one of which is shown in Fig. 2) is greater than 0.89, suggesting that the physical distance measures can be trusted to reflect actual perceptual differences.

The use of a closed-canal microphone system for measuring HRTFs offers significant advantages (e.g., signal-to-noise ratio), since it is simpler and less invasive than the conventional probe-tube system. However, unless measurements can be made without the need for an anechoic chamber obtaining individualized HRTFs will still be impractical. The main problem posed by making acoustical measurements in ordinary rooms is reflections from the walls and floor of the room. These reflections can be eliminated, simply by windowing the recordings, if the distance between the sound source and the ear is small.

We have obtained from another laboratory a large database of HRTFs measured in an echoic room using a closed-canal system with less than 1 meter source-to-ear distance (nearfield system). A principal components (PC) analysis of these data suggests they are quite similar to HRTF data measured conventionally. Figure 3 shows the first 5 PC basis functions obtained from the two data sets. The solid lines are functions obtained from conventionally measured HRTFs and the dashed lines are functions from the nearfield data set. A multidimensional scaling analysis of the differences among HRTFs based on PC weights reveals some interesting differences. Figure 4 shows the results of a 2-D solution in which the stars represent HRTF sets measured conventionally and the squares represent HRTF sets measured with the nearfield system. In this figure HRTFs measured at all elevations are represented, and while there is considerable overlap between the two data sets there is the suggestion of a systematic difference. Figure 5, which shows a scaling solution based only on HRTFs measured at 30 degrees elevation emphasizes the differences and Figure 6, based only on HRTFs measured on the horizontal plane, de-emphasizes the differences. The source of this curious effect is currently under study.

Localization of multiple sources. Natural listening tasks require localization of multiple sources or, perhaps more commonly, localization of a single source in the presence of several other sources. The previous progress report outlined an experiment in which listeners were asked to give apparent position judgments to a single virtual source in the presence of two virtual distracter sources. The positions of the virtual sources were not coupled to the listener's head position. The results of that preliminary experiment indicated that only about half of the subjects tested could perform the task, even when one of the distracters was eliminated. When source position was coupled to listener head position all listeners performed at high accuracy.

Since the last progress report, we have followed up the previous experiment by testing additional listeners and by verifying the localizability of both targets and distracters in free field. On this latter point, both the target stimulus (a wideband noise) and both distracter stimuli, a click train and a harmonic complex, were localized with high accuracy in free field. Figure 7 shows sample data from one listener localizing the noise stimulus. The same pattern of judgements was obtained from nearly all listeners, not only with the noise stimulus but with the click train and harmonic complex stimuli as well.

Localization of a single target in the presence of distracters is a task which reveals large individual differences. Figure 8 shows the data from one listener in the two-distracter condition, suggesting very little effect of the distracters. Figure 9, which shows data from another listener, reveals a substantial degrading effect of the distracters. The degradation caused by distracters is somewhat lessened when only a single distracter is present (Figure 10). While many of these degrading effects of distracter stimuli are reduced when head movement cues are provided, the data are clear evidence of the need to consider display complexity in any kind of mission-critical application of auditory display technology.

Publications

Papers:

Wightman, F. L. & Jenison, R. L. (1995). Auditory Spatial Layout. Chapter 10 in W. Epstein & S. J. Rogers (Eds.), Handbook of Perception and Cognition, Volume 5: Perception of Space and Motion. Orlando, FL: Academic Press.

Wightman, F. L. & Kistler, D. J. (1995). Factors affecting the relative salience of sound localization cues. In R. Gilkey and T. Anderson (Eds.), Binaural and Spatial Hearing. Hillsdale, NJ: Erlbaum (In Press).

Wightman, F. L. & Kistler, D. J. (1996). "Monaural sound localization revisited," Journal of the Acoustical Society of America, Submitted.

Zahorik, P. A., Wightman, F. L., & Kistler, D. J. (1995). On the discriminability of virtual and real sound sources. Proceedings of the ASSP (IEEE) Workshop on applications of Signal Processing to Audio and Acoustics. New York: IEEE Press.

Abstracts

Macpherson, E. A. (1995). "Source spectrum recovery in different spatial locations," Journal of the Acoustical Society of America, **98**, 2946.

Wightman, F. L., Kistler, D. J., Foster, S. H., Abel, J. (1995). A comparison of head-related transfer functions measured deep in the ear canal and at the ear canal entrance. Abstracts of the 17th Midwinter Meeting, Association for Research in Otolaryngology, 71.

Figure 1

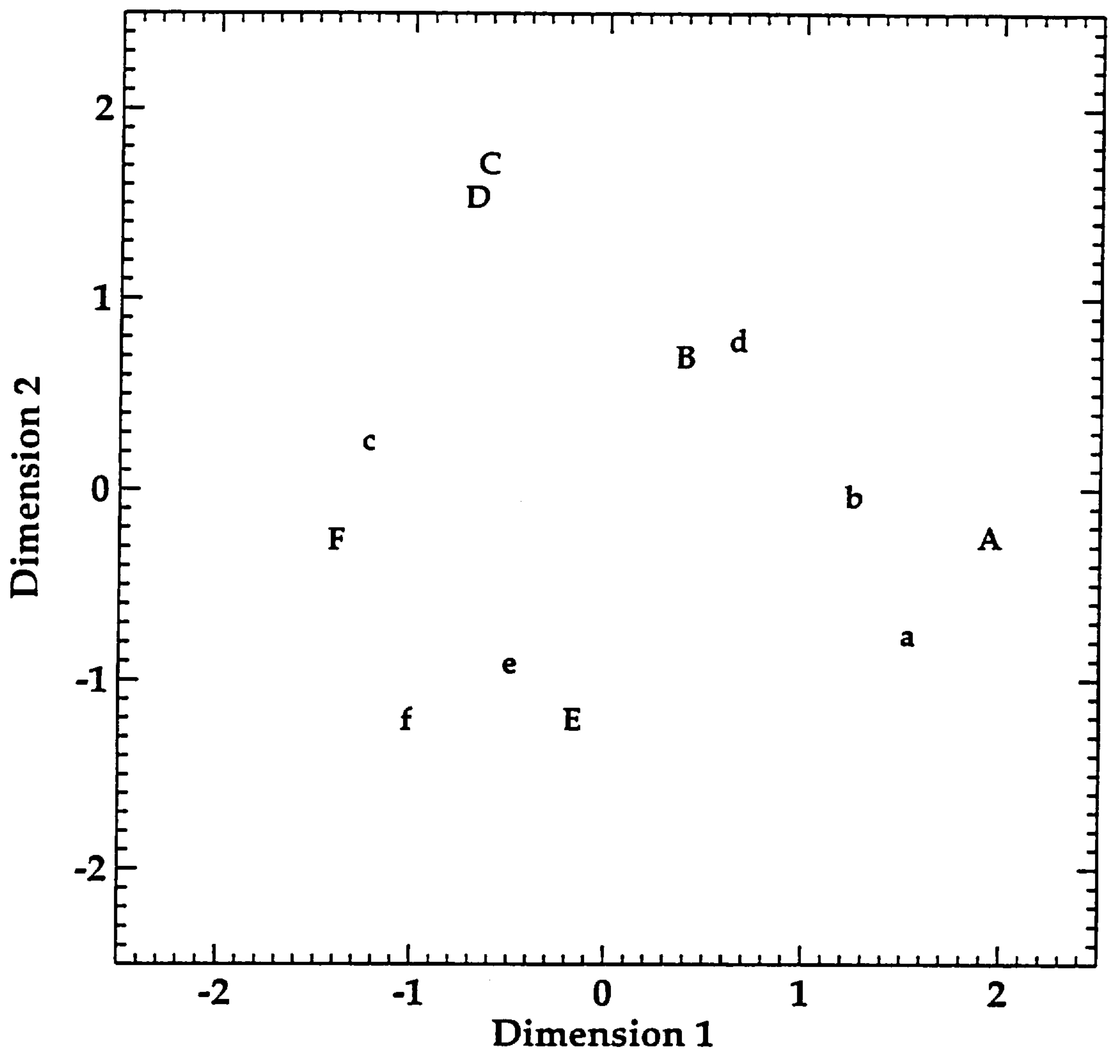

Figure 2

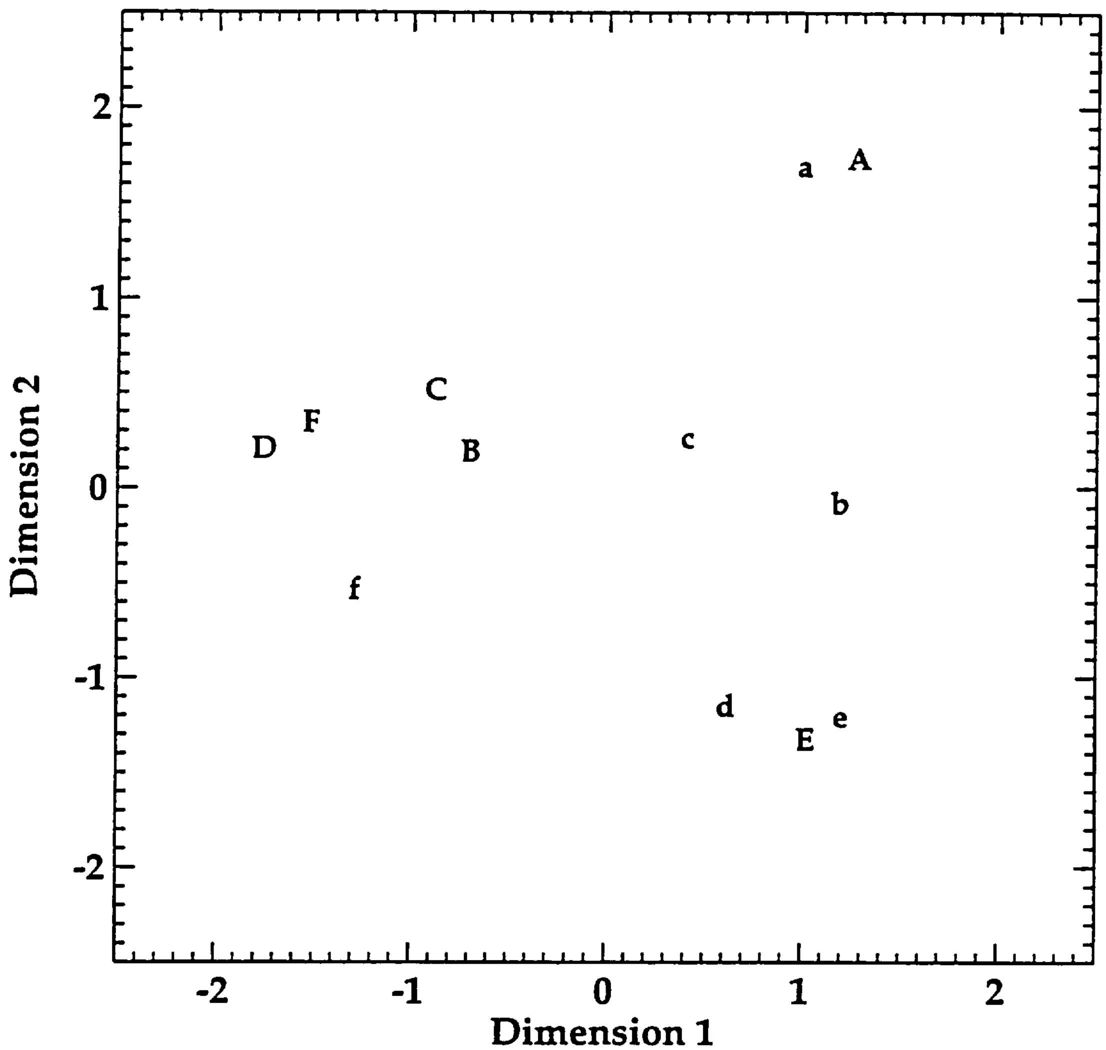

Figure 3

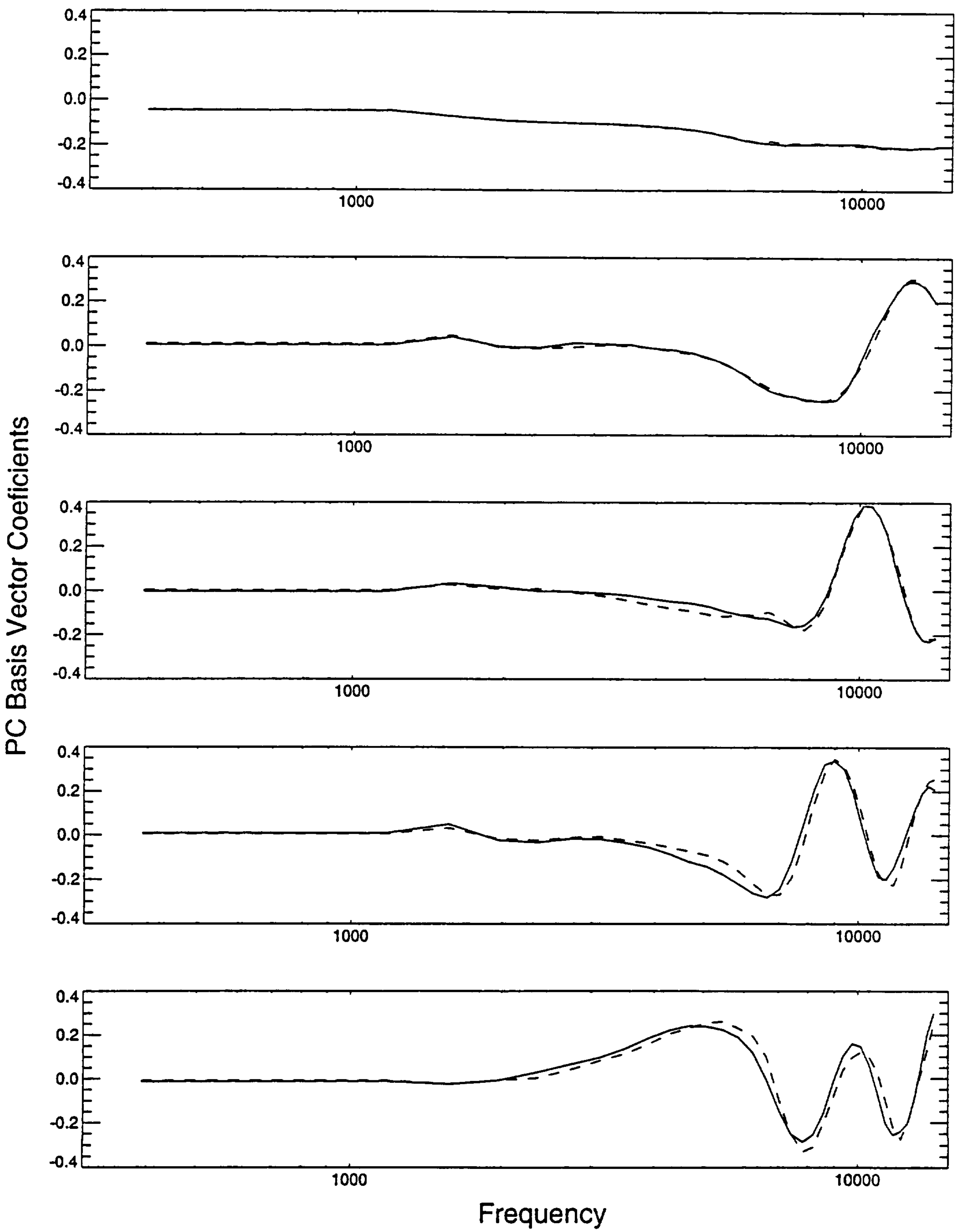
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Figure 4

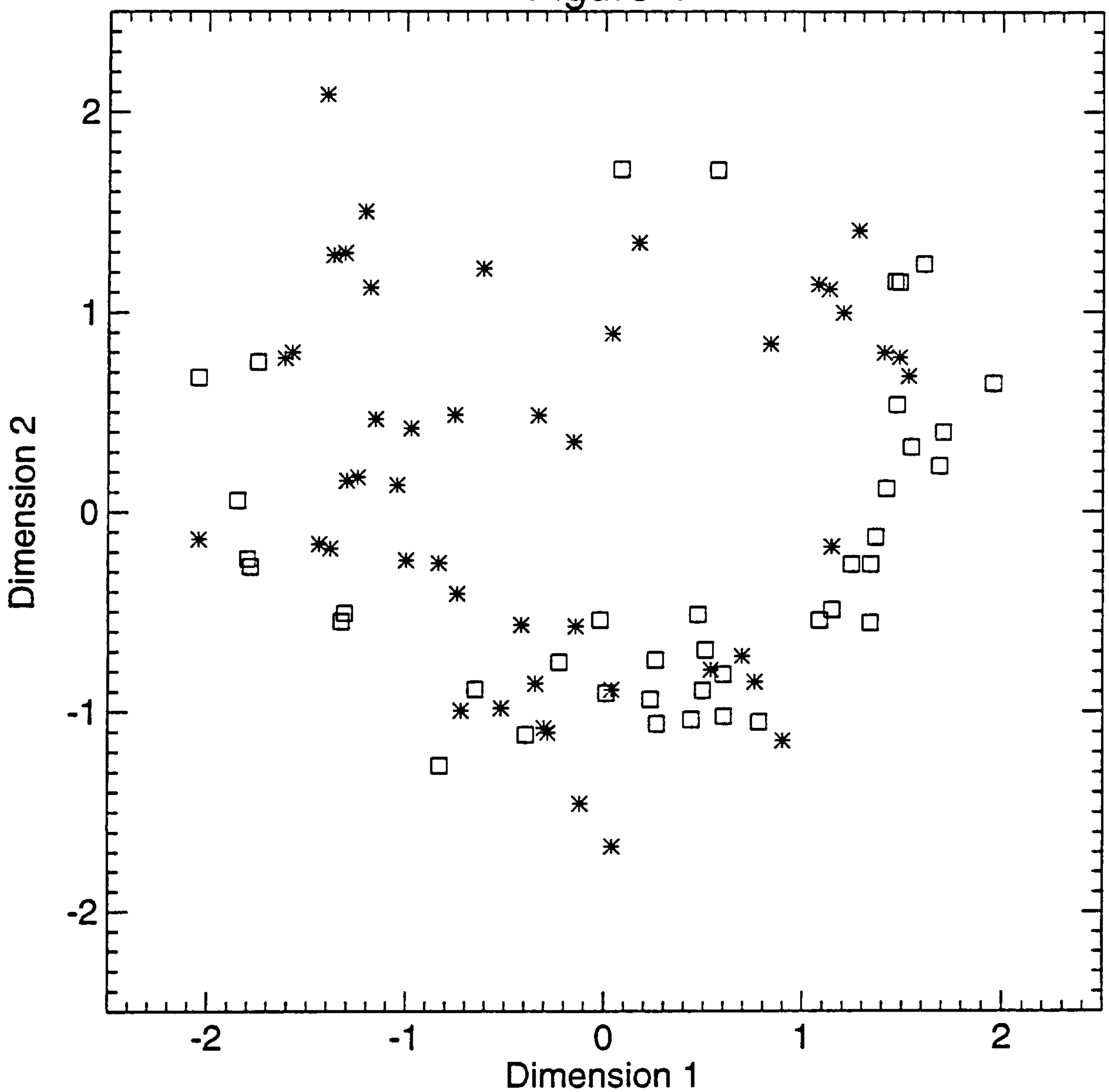

Figure 5

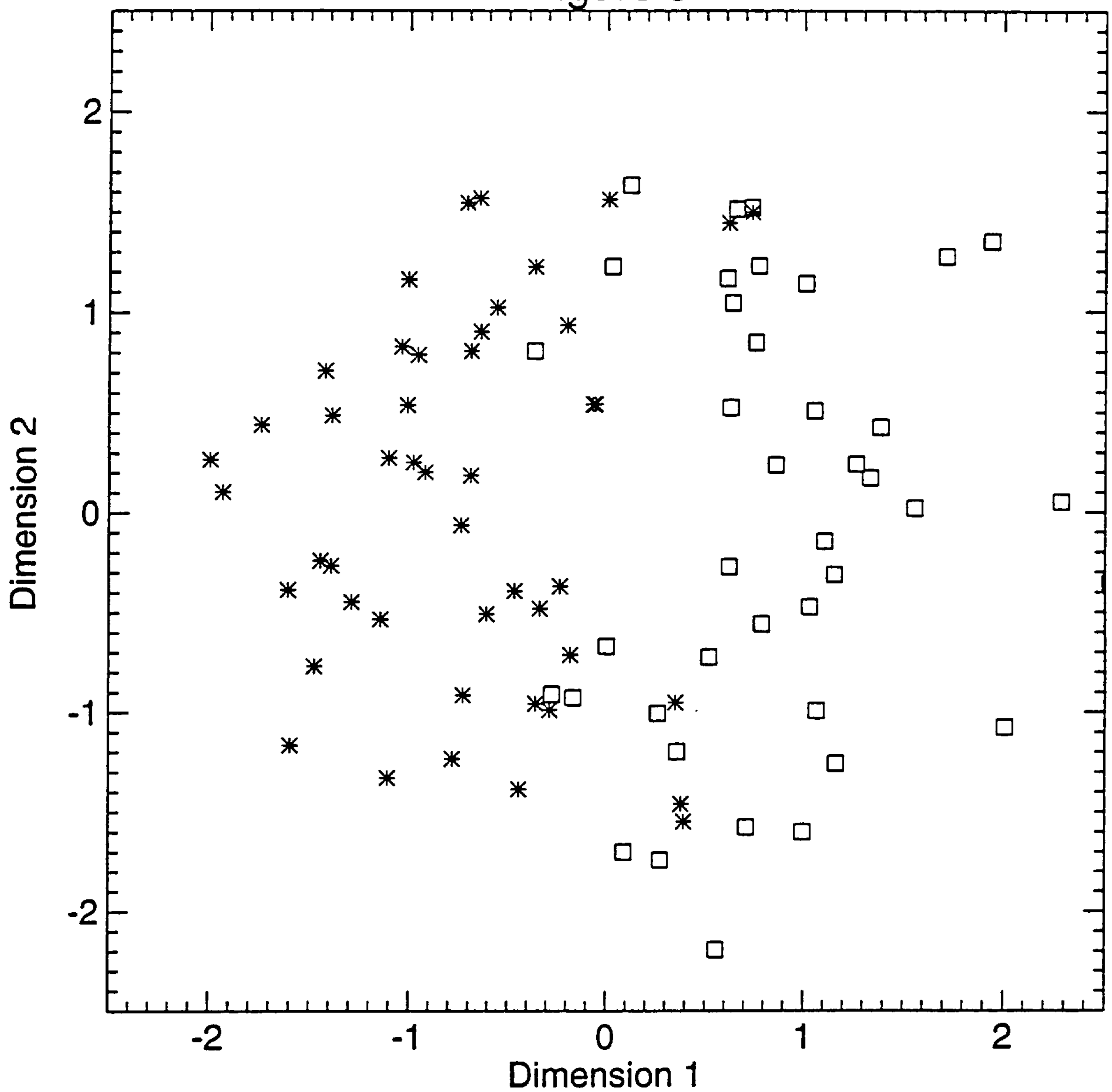

Figure 6

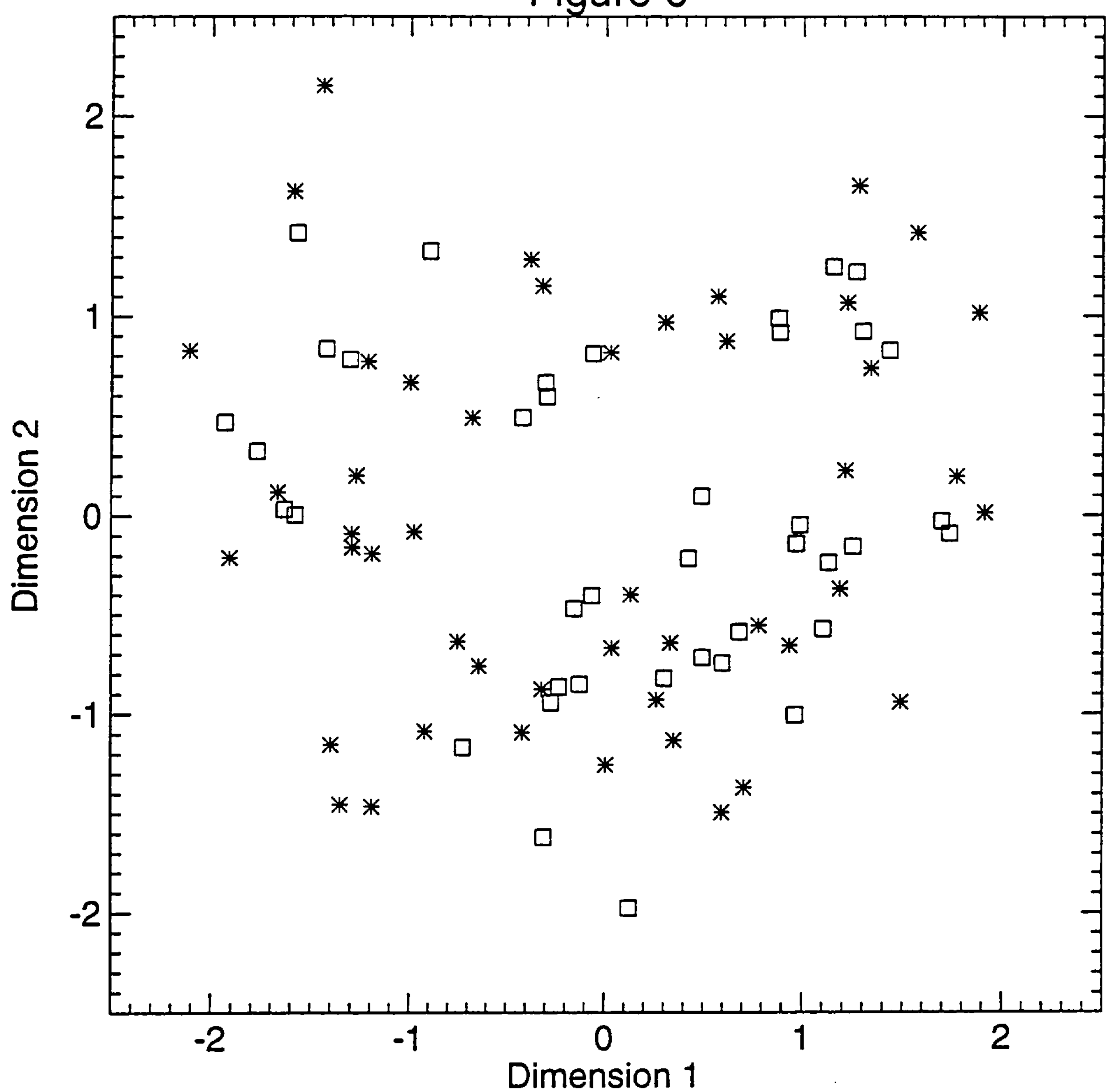

Figure 7

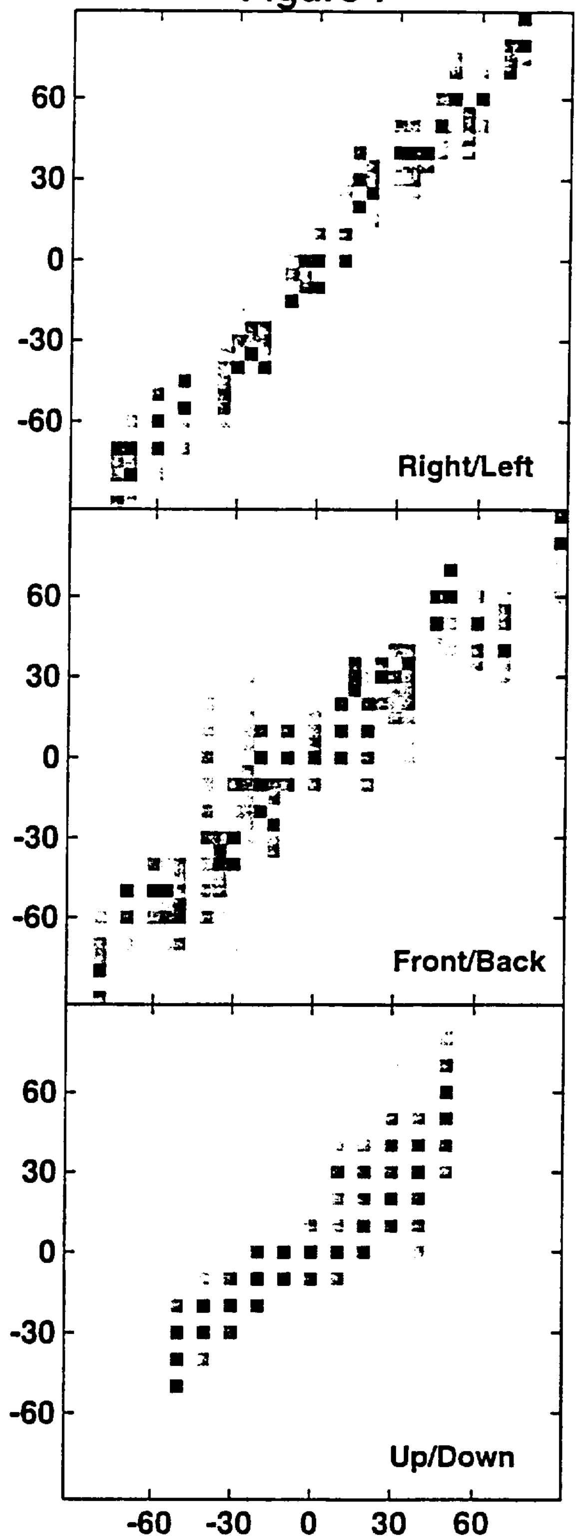

Figure 8

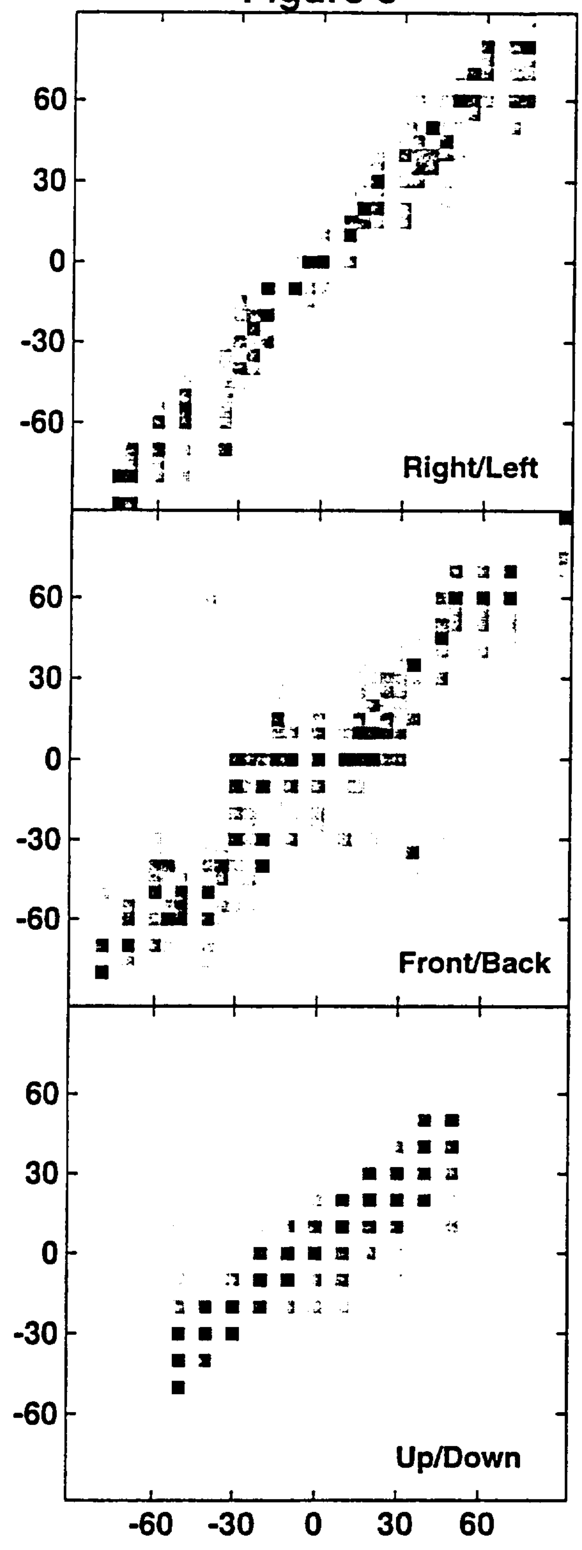

Figure 9

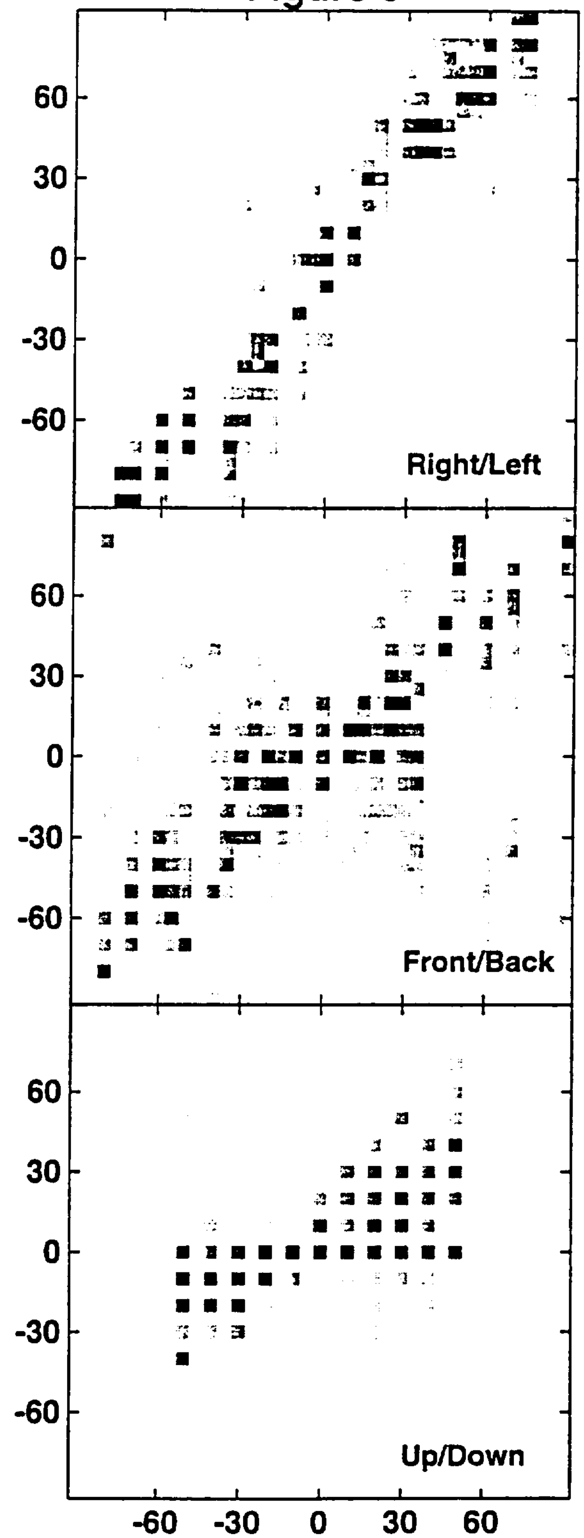

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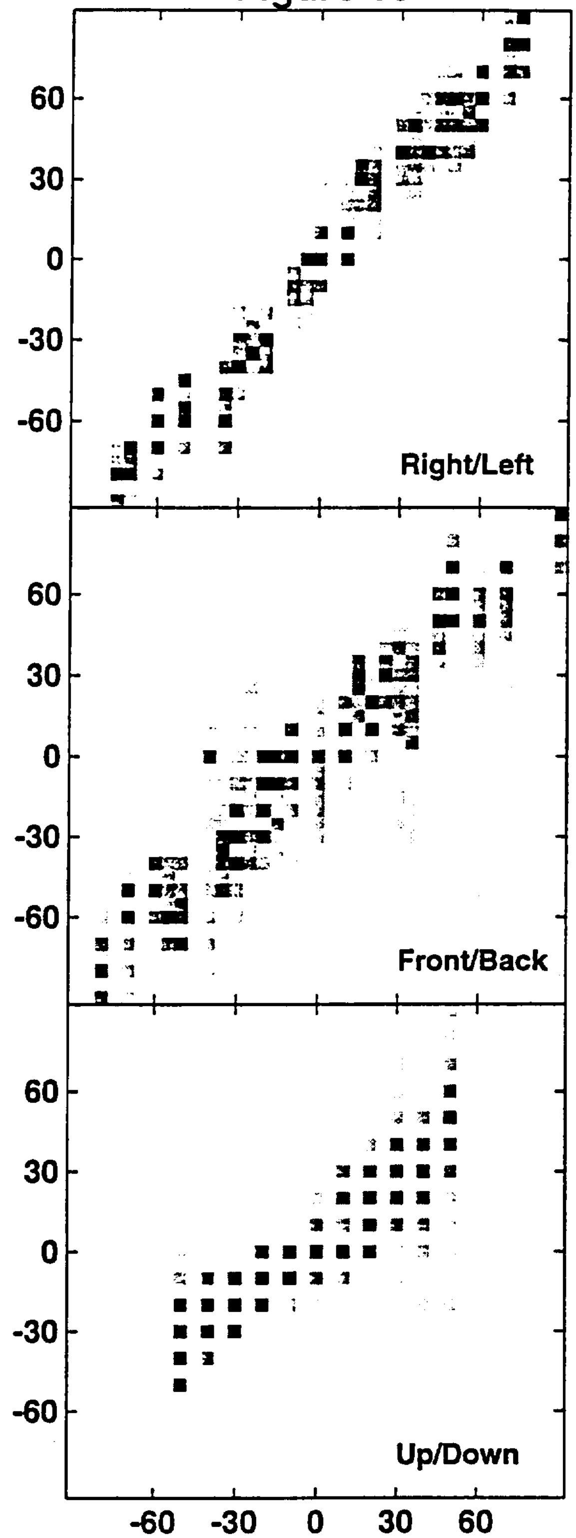
Figure 10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LETTERS AND SCIENCE COMMITTEE FOR THE
PROTECTION OF HUMAN SUBJECTS

Date: September 6, 1995

Name: Frederic Wightman

Department: Psychology

Project Title: "Project on Human Sound Localization"

Assurance Dated: August 15, 1995

Protocol Number: 6-88-25

COMMITTEE ACTION: Approved ______ Not Approved ______ Exempt ______

Approved with contingencies __X__

Hold for additional information ______

Human Subjects Not at Risk __X__ At Risk ______

Review Interval _1 year_

Committee Notes: Please Provide a copy of the consent form currently being used.

ADDITIONAL INFORMATION:

The Letters and Science Committee for the Protection of Human Subjects has reviewed this research protocol on the date noted above. The following information applies to approved protocols:

Consent forms: Sample copies of all consent documents actually used in the project must be provided to the Committee. Subjects who are asked to sign and return consent forms should be given an extra copy to keep for themselves.

Changes to protocol and adverse reactions: New information which may affect the potential risk to subjects must be brought to the Committee's attention in a timely way. Protocol changes must receive the prior review of the Committee.

Continuing review: At the time of its initial approval the Committee set the review interval shown above (one year maximum). Near the end of this interval the Investigator should contact the Committee for continuing review.

Retention of records: It is recommended that signed consent forms be retained on campus for at least seven years following the end of the project.

L&S

COLLEGE OF LETTERS & SCIENCE

MEMORANDUM

TO: Frederic Wightman

From: Donna Jahnke

Date: September 18, 1995

We have received the information you sent regarding your protocol titled "Project on Human Sound Localization"; number 6-88-25. This information complies with the contingencies required by the Human Subjects Committee, and your protocol is now fully approved.

UNIVERSITY OF WISCONSIN-MADISON

■ Office of the Dean ■ 201 South Hall ■ Madison, Wisconsin 53706 ■ Telephone: 608/263-2300 ■

TO: L&S Human Subject Committee

FROM: Frederic Wightman

I certify that there have been no negative reactions from subjects and that the procedures have not changed from those previously approved by the Committee (unless noted below) on my protocol entitled " Project on Human Sound Localization " protocol number 6-88-25E. This protocol is still active and I request that the Committee renew my approval. **A COPY OF THE CONSENT FORM I AM CURRENTLY USING IS ATTACHED.**

Fred Wightman
Signature

15 August, 1995
Date

Changes or negative reactions:

CONSENT FORM

(Protocols #6-88-25, 3-88-12, Rev. 10/15/94)

Projects on Human Sound Localization
and Psychophysical Evaluation of 3-Dimensional Auditory Displays
Frederic L. Wightman, Ph.D., Director

These research studies are concerned with how a human being localizes sources of sound in the environment. You will be asked to take part in one or both of the following two procedures:

1. In order to measure how your outer ear structures affect the quality of incoming sounds, we will use a standard clinical procedure that involves placing a thin (1/32 inch diameter), very flexible silicon rubber tube (probe tube) in your ear such that one end of the tube is very close to your eardrum. While the tube will not touch your eardrum during the measurements, it may touch it when we first insert the probe tube. If the probe tube touches your eardrum you will hear a faint thump (there is no other sensation, and there is no risk of any damage to your ear from the probe tube.) The other end of the tube will be outside the ear and will be connected to a small, lightweight microphone (about 1/2 inch in diameter and one inch long) that is attached with Velcro to a headband. During the measurements, you will be asked to sit comfortably in a chair inside a soundproof room, while sounds are presented from various positions. The levels of these sounds will be moderate, about as loud as traffic noise on a busy street. This part of the project will take about one hour total to complete.

2. You will be asked to sit blindfolded in a soundproof room and listen to sounds presented either over loudspeakers or headphones. After each sound is presented, you will estimate its apparent location. The levels of these sounds will be approximately the same as in the first part of the experiment. This part of the experiment will require at least twenty hours to complete, though you may be asked if you would be willing to continue for an additional twenty hours, or even longer. The entire research project may last several years, though there will be no pressure on you to continue if you desire to stop.

RISKS: The risks to you of participating in this project are minimal. There may be a slight tickling sensation in the ear canal if the microphone tube touches the ear canal walls, but there is no risk of physical damage since the tube is quite soft and flexible. Use of this probe tube measurement system is a standard clinical procedure and will be carried out by a trained audiologist. The second phase of the experiment involves no physical risk, but will probably be somewhat boring.

The results of this study will contribute to our knowledge of how the auditory system functions, but will probably have no direct benefit to you as participant. All of your data, both the acoustic measurements and the localization estimates, will be held confidential. In all probability there will be publications about the results of the study, but they will not contain any material that will identify you as a subject.

Dr. Wightman will be pleased to answer any questions you may have now, or you may call him later, during the study, at 263-3270 with questions or complaints about the research.

Your participation is completely voluntary; you may stop participating at any time prior to the completion of the project. Your decision to participate or not to participate will have no bearing on any treatment you may be receiving at the Waisman Center.

I have read the above and give my consent to participate in the study.

________________________________ ________________

Signature Date

CURRENT AND PENDING RESEARCH SUPPORT

Source of Support	Project Title	Principal Investigator	Percent Effort	Annual Direct Costs	Entire Period

F.Wightman, Current:

NIH R01HD23333-07	1	F. Wightman	20	8/1/95-7/31/96 $82,037	8/1/92-7/31/97 397,765
NIH P01DC00116-20 Project 5	2	J. Brugge	25	3/1/96-2/28/97 $107,414	3/1/94-2/28/99 536,951

F. Wightman, Pending

ONR	3	F. Wightman	10	uncertain

D.Kistler, Current

NIH P01DC0016-20 Project 5	2	F. Wightman	55	3/1/96-2/28/97 $107,414	3/1/94-2/28/99 $536,951

D. Kistler, Pending

ONR	3	F. Wightman	10	uncertain

Titles of Research Projects:

1. Hearing Assessment in Pre-school and School-Aged Children.
2. Research Program on the Neural Basis of Hearing (Subproject 5).
3. Enhancing Situational Awareness with Virtual Auditory Displays.