# Sound Increases Sensitivity to Signal Detection in 2D Plots of Numerical Data

**Wanda L. Diaz-Merced,**
**Stephen Brewster**
Glasgow Interactive Systems Group
School of Computing Science
University of Glasgow
Glasgow UK G12 8QQ
wanda@dcs.gla.ac.uk
stephen@dcs.gla.ac.uk

**Robert M. Candey**
NASA GSFC
1800 Greenbelt Road
Greenbelt
Maryland 21222, USA
Robert.m.candey@acm.com

**Matthew Schneps**
Laboratory of Visual Learning Harvard Smithsonian Center for Astrophysics
60 Garden Street
Cambridge MA 02138, USA
mschneps@cfa.harvard.edu

**Marc Pomplun**
Visual Attention Laboratory
University of Massachusetts
100 Morrissey Boulevard
Boston,MA 02125-3393
marc@cs.umb.edu



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## Abstract

Current analysis techniques for 2D astrophysical numerical data are based on standard visual techniques. Astrophysics data acquired from the interstellar medium may contain events that may be masked by noise making it difficult to identify them. We present results from an ongoing project to investigate the use of non-speech sound as an adjunct to visualization to improve the identification of changes in graphical representations. We compare the results of identification using audio rendering only and visual only with combined audio and visual. Results showed that just combining audio and visual displays did not improve identification performance. Performance improved significantly when an extra cue was included. The extra cue being a red line sweeping across the visual display at the rate the sound was played. Results show peoples performance improves when the multimodal displays are synchronized.

## Author Keywords

Visualisation, multimodal perceptualisation

## ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

## General Terms

Human Factors

## Introduction

The interest in exploring the potential of using sound encoding of numeric data has increased (see papers published at ICAD.org). In space physics, data sets are acquired from the natural laboratory of the interstellar medium. Each event in the interstellar medium is the product of an amount of oscillatory modes. Those events may be quasi-periodic, non-persistent, masked by noise, fleeting etc. Traditional techniques for the analysis of space physics data (e.g. radio, particle, magnetic fluctuation, X-ray, to mention some) are based on visual exploration of data. Additionally, various nonlinear time-series-analysis methods were designed for nonlinear but stationary and deterministic systems. Space scientists base the data analysis on fitting the data to waveforms determined by the problem at hand, linearizing and/or stationarizing the data (mean and variance do not change if they exist). Unfortunately, in most real systems, either natural or human-made, the data are most likely to be both nonlinear and non-stationary.

Space physics and its graphical representations have mostly been visual and or unimodal. The quantities of space physics data collected from the interstellar medium are always increasing saturating the visual perceptual system. Another limitation is that even the best computer screens available are limited to a range of spatial resolution. This limitation affects the useful dynamic range of the display, reducing the amount of data scientists can study at any one time. Scientists currently work around this limitation by filtering the data, so as to display only the information they believe is important to the problem at hand. But since this involves making some a priori choices about the result they are searching for, discoveries may be missed.

It has been proved by Magnetic Resonance Imaging [15][14], that task load in the periphery of the visual field suppresses perception in the center, and task load in the center is found to affect detection in the periphery, suggesting that the centre and the periphery interfere under attention task load [3],[7],[12],[13]. The always increasing sampling rate of space science data, generate data sets comprised of up to hundred of thousands of data points. The scientifically interesting part of the data or signal may be anywhere in a data set. This data is characterized by the presence of noise,[16] which is always present. Most of the time knowledge is available on the detectors noise so the noise may be filtered (*e.g.* common noise distribution is determined by its variance) to remain with signal, and it has to dedifferentiated from noise or clutter [17]and by definition is not compressible. The signal may be non persistent, fleeting, quasi-periodic, masked by the noise and for that reason noise is estimated, and then filtered from the data. Astronomy calls for the holistic integration of visuospatial extended information, sensitivity to fleeting changes occurring away from the direction of gaze and masked by noise. The experiments in this section, determined the signal-to-noise (S/N) thresholds for which participants could correctly identify the presence of a simulated double-peaked “black hole” pattern that was obscured by visual and audio Gaussian noise. In the case of our task, the high-spatial frequency noise (overlying the low-spatial frequency “signal”) may act as a cognitive load that triggers mechanisms of attention that inhibit peripheral sensitivity. Though it may be difficult to precisely demarcate a center– periphery boundary, for the purposes of this discussion, and after literature review, in the experiments presented the center to periphery boundary is taken to be at ~8°, where changes in attention response become pronounced [11] [15].

The experiments presented here are based on the empirical measurement of performance based on correct answers. For this purpose, the visual Black Hole paradigm designed by Schneps and Pomplun [14], was modified. They experimentally determined the visual signal-to-noise (S/N) thresholds for which participants could correctly identify the presence of a simulated double-peaked “black hole” pattern that was obscured by visual

| ion | Exp. 1 NDV | Exp. 2 NDV | Exp. 3 DV |
|---|---|---|---|
| Only | x | x | X |
| Only | x | x | X |
| and Audio ed Line | | x | X |
| and audio | x | x | X |

eriment vrs Conditions

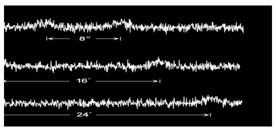
Gaussian noise. The paradigm was modified to evaluate participants performance when experiencing audio and visual presentation of the same type of simulated double

peak data. Three experiments were conducted. Experiment one, consisted on the presentation of 3 cues: a) Visual, b) Audio, c) Visual and Audio together. Visual stimuli presented at static visual angle of 8 degrees for 1000ms and Synched with the sound. Given the results of experiment 1, experiment 2 consisted in the presentation of 4 cues ( see experiment 2 section **for more details)** that serve as stimuli: a) Visual, b) Audio , c) Visual and Audio together with a red line sweeping across the spectra at the rate the sonification is played, d) visual and audio together. Visual stimuli presented at static visual angle of 8 degrees for 1000ms and synched with the sound. Given the results of Experiment 2, experiment 3 consisted in the presentation of 4 cues (see experiment 3 section **for more details)** that serve as stimuli: a) Visual, b) Audio, c) Visual and Audio together with a red line sweeping across the spectra at the rate the sonification is played, d) visual and audio together. Visual stimuli presented at a dynamic changing visual angle of either 8, 16 or 24 degrees for 1000ms and Synched with the sound. The three experiments performed to compare user performance when trying to identify the presence of signal in the presence of masking noise when experiencing each of those cues. The users responded to the cues using the keyboard and a threshold analysis using an algorithm called QUEST (Quick Unbiased and Efficient Statistical Three [11]) was used to calculate accuracy in the form of thresholds. A staircase algorithm monitored the responses and dynamically varied the amplitude of the "signal" Gaussians until a threshold at which participants responded correctly in 75% of the trials could be ascertained (determined each subject’s 75% threshold sensitivity for the correct identification for each condition). A Bayesian adaptive staircase procedure [21] which uses all previous trials to estimate the parameter T, the threshold, in the psychometric function was used to measure S-N sensitivity thresholds in the black hole task for each of the three span conditions in the task (8°, 16°, and 24°).

The experiments presented in this section investigates the hypothesis that sound as an adjunct to data visualization will help participants to allocate signatures (identify the presence of a simulated double-peaked “black hole” pattern) in simulated black hole space physics data. The research used a task simulating the process astronomers use to search for the characteristic indicators of black holes. The task derives from the idea that a Black Hole exists in the center of each galaxy. The molecular gas around the Black Hole emits a symmetric double peak spectrum that is characteristic of the presence of a Black hole. This signal was simulated for our experiment.

### Experiment Description

Auditory stimuli were presented through headphones Sennheiser HD 215 headphones. The volume of the sounds was adjusted to ensure participant comfort by 0 to 4dB. Stimuli were presented on a 20-inch Apple Cinema flat-screen LCD monitor viewed at a distance of 70 cm, with a resolution of 1680 by 1050 pixels and a refresh rate of 60 Hz. Stimulus presentation and data acquisition were controlled by custom software using Matlab (The Mathworks, Natick, Massachusetts), and the Psychophysics Toolbox (Brainard 1997).Visual and Audio graphs of artificial “radio spectra” served as stimuli in the present study. The visual stimuli (visual graph), based on the paradigm designed by Schneps and Pomplun **[14]** was shown as a white line (luminance: 360 cd/$m^2$) on an otherwise black screen (3 cd/$m^2$). The width of this line was approximately 0.1° of visual angle, and the graph subtended 30° horizontally and 3° vertically. In ‘noise-only’ stimuli, the vertical position of the graph at each horizontal pixel position was determined by Gaussian noise, and the graph was scaled to subtend 3° vertically. In ‘signal’ stimuli, a signal consisting of two positive (upward) peaks was added to the noise before the scaling was performed. These peaks were modeled by identical Gaussian functions with standard deviations of 0.5° and




l example of visual cue ed to participants; ngle of span 8, 16 and

variable, but equal, peak elevation. The quotient of peak elevation and standard deviation of the Gaussian noise in a given stimulus was operationally defined as its signal-to-noise ratio (S/N). The two peaks always occurred to the left and to the right of the center at identical eccentricity. The span separating the peaks was 8° for experiment 1 and 2 and 8°, 16°, or 24°, with random jitter in the span modeled by Gaussian noise with a standard deviation of 1.0° for Experiment 3.

The code translated the continuous visual stimuli,( noise, signal + noise), into sound. The sound was created by using a weighted sum of the square wave and sine waveforms. the audio signal vary between sine wave and square wave, so that a low value in the radio spectrum would lead to sine wave, and a high one to square wave.

The sonification of the data is defined by the following parameters:

1.waveform modulation = 0 (if no waveform modulation, this is the waveform being used (0 = sine, 1 = square).

2. stereo = 0 (no pan stereo = 0)

3.fadeDuration = 0.07;

4.cf = 880 (carrier frequency for amplitude modulation (Hz))

5.mf = 110 (minimum frequency for pitch modulation)

oct = 6 (octave range for pitch modulation)

sf = 22050

The participants performed five blocks of trials, for each condition, in random order. Each block consisted of 15 trials, with the presentation of each spectrum for 1000 ms. Participants were instructed to press the ‘S’ button on a computer keyboard if they believed that the current spectrum contained a signal and to press ‘N’ if they thought that there was no signal. There was no time limit for the participants’ response. Immediately after pressing the button, participants were acoustically informed whether their response was correct (800 Hz sound played for 20 ms) or incorrect (400 Hz sound played for 100 ms). Participants were allowed to move their eyes freely throughout the experiment and their heads were positioned with their heads centered on the screen, on a chinrest for comfort at 70 cm from the screen. The first trial in each block presented a signal at a signal-to-noise ratio of 10, which was very easy to identify. The remaining trials were aimed at estimating the signal-to-noise threshold at which the subject gave correct responses in 75% of the trials. This estimation was performed using the QUEST staircase procedure [21] with an initial threshold estimate of 1.5 and parameters $\beta = 3$, $\delta = 0.01$ and $\gamma = 0.3$. The threshold update between trials was based on the quantile method and the final estimate was determined by the mean method [8].

## FIRST EXPERIMENT: 3 CONDITIONS ND

The first experiment created the baseline. Separation of the Gaussians was 8° with equal eccentricity. Eleven space scientists age 20-45 took part in the study. None of the participants had participated in our experiments before. They were recruited via e-mail to scientists at the Center for Astrophysics in Massachusetts and through personal contacts. They were paid $10 an hour in Amazon gift certificates upon completion of the experiment. Participants were screened for normal or corrected-to-normal vision and hearing, accurate color vision, normal cognitive function, and no history of neurological disorder. All the participants were PhD space scientists with post PhD publications.

This experiment observes the effect of conditions 1 (visual cue only),2 (audio cue only), and 3(visual and audio together), on performance (described above) towards the hypothesis that sound as an adjunct to visualization may help space scientists to identify signatures in space physics 2D numerical graphed data.

After the instructions were declared, the participants were encouraged to ask questions. Once they had understood the task, a five minute practice session followed, in which the participants took part in the experimental conditions. The practice consisted on the same conditions as the main experiment and served as a baseline for the volunteers. All subjects gave informed consent according to procedures approved by the Harvard University Research Subjects Review Board.

### Experiment One ND[1]

An artificial black hole "signal" consisting of a pair of symmetrically placed Gaussians separated by fixed span of 8°, where changes in attention response are more pronounced, to which a variable amount of Gaussian-random noise was added. The latter was displayed either visually on a computer screen and/or in sound through headphones. Participants were shown either a "signal" or "noise" as an image flashed on the screen and or audio for 1000 ms. Participants pressed a key to register their yes/no responses to indicate whether they believed the spectrum presented contained "signal" or "noise"

In the visual condition a graph was shown on a screen and participants asked to indicate whether or not a signal was present. The auditory condition were the same, except that participants heard a sonified version of the graph. In the visual+auditory condition, participants were presented with both modalities simultaneously. The experiment took approximately 45 minutes.

| to- res ld nd. | S-to-N Thresh old cond.2 | S-to- N Thres hold cond. 3 |
|---|---|---|
| 60 | .784 | .651 |

xperiment 1 Mean thresh- conditions: 1=visual; 2= visual and audio.

### *Results experiment 1*

A repeated-measures one-way ANOVA, based on correct of responses over the three conditions, was conducted to observe the effect of Conditions 1,2,3 on the participants' and individual differences in performance, the authors calculated the, distribution of mean for the threshold per condition. The mean distribution N=11 favored condition 1) over condition 2) and 3). Equally the mean distribution favored condition 3) over condition 2). The results produced no significance $f(1.5, 14.7)= .806$ $p = .215$.

None of the conditions (1,2,3) differed significantly. The volunteer's verbalized Conditions 2 and 3 were harder at the beginning because they were not used to it. All the participants said they felt conditions 2 and 3 were more useful as the S/N ratio decreased.

### SECOND EXPERIMENT 4 CONDITIONS ND

The second experiment explored the effect of another information input on performance. The fourth stimuli being a redline sweeping across the visual graph at the rate the sonification was played (visual and audio presentation synchronized with a red line sweeping across the graph at the rate the sonification was played), to compare user performance. The authors hypothesized that a moving target on the screen may induce attention allocation, leading to audio-visual capture that will help towards the identification of the Black Hole signal in the data, specially when the signal to noise ratio is really small. It was predicted that space scientists using sound as an adjunct to visualization and a third congruent cue (the red line sweeping across the spectra) would be able to detect the presence of "signal" at lower S/N thresholds as compared with the space scientists participating in the first experiment.

The moving line functions as congruent stimuli that may elicit attention control [19]. The red line is intended to force audio/visual capture in which the perception of the sound as coming from the red line position on the screen, due to the influence of visual stimuli [20]. In this experiments the noise masks the signal so the signal to noise ratio is very small, leading the visual signal to be ambiguous when present. It has been demonstrated in the literature [19] that congruent auditory or tactile information, and combined auditory–tactile information, aids attention control over competing visual stimuli and vise versa. Van Ee also found that congruent sound aids

[1] ND=No dynamic visual

| | S-to-N Thrshld cond.2 | S-to-N Thrshl d cond.3 | S-to-N Thrshl d cond.4 |
|---|---|---|---|
| | .784 | | .651 |
| | 0.6 | .54 | .51 |

Display of experiment 1 (3 s) Average threshold and nt 2 (4 conditions) average . Condition 1=visual; Con- audio; Condition 3= visual ) with red line; Condition and audio

| al o | Audio vsBoth Red-Line | vs BothRed-Line vs Both |
|---|---|---|
| | 0.53 | 0.25 |

Effect Size experiment 2 (4 ons No Dynamic Visual)

attention control over visual ambiguity and correspondingly a congruent visual pattern aids in control over ambiguous sounds. In this experiment these findings are used as a framework to add the red line as a third modal cue and observe the effect of this third cue on participant performance. The BlackHole paradigm designed towards the three experiments presented in this paper is a dynamic task requiring participants to divide attention among multiple dynamically changing stimuli (signal to noise ratio changing)[4]. It is expected the third stimuli (red line) will give the participants a means to allocate attention to correlate the audio to a particular part of the visual graph. Resulting on performance improvement as

compared with the first experiment.

Separation of Gaussians was fixed at 8° with equal eccentricity. The experiment again used a within subjects design, and the settings, instructions and design were the same as those of the first experiment with the exception that the fourth (red-line) cue was added. 14 participants, age 20-45, from the Center for Astrophysics participated in the experiment. None of the participants had participated in the experiments before. They were recruited via an email to scientists at the Center for Astrophysics in Massachusetts and personal contacts. They were paid $10 an hour in Amazon gift certificates upon completion of participation. Participants were screened for normal or corrected-to-normal vision and hearing, accurate color vision, normal cognitive function, and no history of neurological disorder. All the participants were PhD space scientists with post PhD publications. The experiment took 50 minutes.

## Results Experiment 2

A repeated measures one-way ANOVA, based on correctness of answers to observe the effect of conditions 1,2,3,4, ND as a condition of the experiment resulted in significance across the four conditions $f(2.19, 28.5) = 4.83$ $P < .012$ ; $p<.05$.

The result above shows there is a significant difference in mean values across the four experimental conditions. The paired difference table to show contrast shows significant differences for conditions 1 vs. 2, conditions 1 vs. 3, conditions 2 vs. 3, and conditions 2 vs. 4 (see table 7). The difference between the Visual and Audio was a larger effect, between Audio and Both Red Line is a comparatively medium affect and between Both Red Line and Both is a relatively medium effect.

Participants verbalized the red line was a distraction as they knew where to expect the signal. As they know it is symmetric then the red line becomes a distraction because they focus on the sound; they said they do not need the position marker. Participants also verbalized improvement in their correct answer rate as the experiment progressed.

## Conclusions Experiment 2

The BH task presents the data for 1 second. In this time a person can perform at most 4 fixations and because the signal is fixed at 8 degrees of visual angle, participants said that the sweep-line becomes nothing more than a distraction adding to their cognitive load. (They knew the visual location of the signal on the data) The reader should note that experiment one lead to no significance (see table 4 to compare the mean thresholds

per condition) One hypothesis is that the volunteers were implicitly using the sweep-line, if that is the case it helped the user understand where they are in the context of the entire data set. In effect, the combination of the sweep-line and the auditory information is acting like a high-pass and low-pass filter. Then the sweep-line provides information about the slowly varying content, while the auditory information helps users understand the underlying, rapidly varying data. If that is the case then if the position of the Gaussians change randomly as the signal to noise ratio change (for instance making the visual cue more ambiguous at times) an improvement in performance or signal detection is expected.

'isual Auditory
BothRed- BothRed-
tory e e vs Both

.495
0.9633 0.36

e 5 Experiment
fect Size ( 4
litions Dynamic
al)

## THIRD EXPERIMENT: 4 CONDITIONS DV[2]

The third experiment explores the effect of use of multi-modal (audio and visual) interaction to explore the effect of the use of sound as an adjunct to visualization on exploring data masked by noise for which signal position is randomly iterated. [3]Iterating the separation of the two Gaussian signal by 8°, 16° or 24°. The latter introduces the condition in which subjects don't know what stimulus eccentricities to expect. In that case they would actually have to analyze symmetry (e.g. just as, the space scientists have to do it when looking for black holes). 12 volunteers space scientists age 20-45 were recruited and screened as for the first and second experiments. None of the volunteers had participated in our experiments before. Experiment settings and cues were as for experiment 2 with the exception that the position of the signal was dynamically iterated to angles of 8°, 16° and 24°

### Results

A repeated measures one-way ANOVA, based on correctedness of responses to observe the effect of conditions 1,2,3,4, DV as a condition of the experiment resulted in significance across the four conditions: $f(2.11,23.21) = 3.47$ $p=.009 < .05$. Mean variance analysis S=12, N=60 produced significance across the four conditions $p = .009$. Condition 3) was favored over condition 1), 2) and 4). (see table 6)

Participants reported the red line forced them to listen and see in a particular order. It has to be researched if participants were incidentally using the red-line. Equally 8 of 12 volunteers reported it was not hard to use condition 3. The result of Experiment 3 shows that performance is significantly affected by the conditions. Report on effect size indicates a large effect between Auditory and Both Red Line, a medium effect between visual and auditory and a medium to effect both and both with Red Line. The Visual/Audio capture was shown to cause a larger effect on experiment 3 Dynamic visual, which tended to mimic the kind of scene space scientists face when analyzing 2D data. Future research could explore whether a carefully designed training session would result in the visual and audio capture to be more significant.

Some participants verbalized to develop a technique to use the red line. They asserted the red line forced them to listen and visualize in a particular order. Equally 8 or 12 volunteers reported it was not hard to use conditon 3.

It is interesting to notice that the participants found it difficult to transition from condition 1, to any other condition. Specifically when condition 1 was the first block of condition experienced in the experiment because they were not used to it. After they got used to it, it became easier. The reader should remember the order of the conditions were completely random (8, 16 or 24

degrees of visual angle).

Participants reported relying more on the sound as the experiment progressed. As the order of conditions was random and visual angle iterated as signal to noise ratio varied accordingly participants could not develop automaticity. One participant said to close the eyes when signal to noise ratio was visually ambiguous, to make sense of the cue, because it is the stimuli s/he may control (on/off), none of the participants removed the headphones at anytime. A particular participant reported to open and close the eyes when ever the condition had sound. Another participant reported to close his eyes not to pay attention to the visual cue. All the participants reported that they developed a technique to scan the data during conditions 2, 3, and 4. They reported that they listened the sound only focusing on a particular change especially when the signal to noise ratio got very low (visually confusing/ambiguous), they listened for one characteristic change in the data and if it was present, they then relied on there being a second symmetric lump. Equally all the participants reported that they

[2] DV=Dynamic Visual

| | Thresh old | Std. De-viation | N |
|---|---|---|---|
| | .6554 2 | .157803 | 12 |
| | .6330 0 | .115934 | 12 |
| d h | .5314 2 | .112911 | 12 |
| d | .5489 2 | .148118 | 12 |

Experiment 3
olds 4 conditions
ic Visual ( DV)

replayed the sound in their heads when not certain for conditions 2,3 and 4. Participants mentioned that they relied on the visual if the signal to noise ratio was high, with rely meaning to answered faster and did not to replay the sound in their head.

About condition 1, the volunteers reported they had a mental image of the red line. In general for condition 2 and 3, and 4 they got the pattern then figured out the signal, played it back in their head quickly looking for the signal and then, used their eyes to look for it.

In general the volunteers said the red line helped specially if the signal to noise ratio was very

## Conclusion

As mentioned earlier, the red line together with the audio cue helps the user to understand where they are in the context of a large data set varying in content. In that regard the redline together with the sound helps the user to make sense of the visual cue as it causes a visual capture, that at the same time causes for the participant to orientate in the context of a large data set varying in content. This is especially evident in very low signal to noise ratio, which makes the signal (if present) ambiguous. The signal visual angle varied 24, 16 and 8 degrees, meaning from center of visual field to the periphery. As attention to the periphery inhibits attention to the center of visual field and vice versa, the improvement in performance in signal detection evidenced in experiment 3 may be an indicator that sound as an adjunct to visualisation when a third multimodal cue (red line) helping to allocate attention mechanisms is added, does help our target audience increasing sensitivity to signal detection, when the signal is ambiguos and located at different visual field angles.

It is very interesting to note that people reporting to develop techniques to listen may have been using memory in advanced ways to compare patterns observed to patterns memorized. People with poor memory cannot use such strategies. This could be an interesting theme to research on effective displays.

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