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Virtual Wayfinding Using Simulated Prosthetic Vision in Gaze-locked Viewing

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Abstract

Purpose—To assess virtual maze navigation performance with simulated prosthetic vision in gaze-locked viewing, under the conditions of varying luminance contrast, background noise, and phosphene dropout.

Methods—Four normally sighted subjects performed virtual maze navigation using simulated prosthetic vision in gaze-locked viewing, under five conditions of luminance contrast, background noise, and phosphene dropout. Navigation performance was measured as the time required to traverse a 10-room maze using a game controller, and the number of errors made during the trip.

Results—Navigation performance time 1) became stable after 6–10 trials, 2) remained similar on average at luminance contrast of 68% and 16% but had greater variation at 16%, 3) was not significantly affected by background noise, and 4) increased by 40% when 30% of phosphenes were removed. Navigation performance time and number of errors were significantly and positively correlated.

Conclusion—Assuming that the simulated gaze-locked viewing conditions are extended to implant wearers, such prosthetic vision can be helpful for wayfinding in simple mobility tasks, though phosphene dropout may interfere with performance.

Keywords

low vision; low vision rehabilitation; prosthetic vision; retinal prosthesis; simulation; wayfinding; mobility; orientation

In recent years, retinal prostheses have been developed in an effort to restore some functional vision in those who have outer retinal blindness.^{1–3} Retinal prostheses in the near future will likely remain limited to a small number of electrodes (<100) with diameters of 100–500 μm and spacing of 300–800 μm .^{4–6} The electrode size and spacing determine that the spatial resolution of early prosthetic vision will be much lower than normal vision, on the order of 20/2000 at best. A question thus arises: Even if each electrode elicits a distinct phosphene, can such low-resolution vision be useful in orientation and mobility? Studies have been done to estimate minimum requirements for the resolution of prosthetic vision to perform mobility tasks.^{7–10}

Our laboratory previously investigated wayfinding performance of normally sighted subjects in simulated prosthetic vision of 6×10 phosphenes covering a visual field of $27^\circ \times 16.2^\circ$.¹⁰ The quality of simulated prosthetic vision in that study was manipulated with three parameters, luminance contrast, visual background noise, and phosphene dropout. Those three parameters

have been reported to play a central role in prosthetic vision.^{4,11-13} Luminance contrast is important for image quality and is affected by pulse duration and charge density.¹⁴ The sensation of spark-like background noise is often reported by patients with late-stage retinitis pigmentosa.^{15, 16} Phosphene dropout in the pixelized image of prosthetic vision can be a result of malfunctioning electrodes or an unresponsive retinal patch underneath the electrode array. In our previous study, subjects traversed a 10-room virtual maze with simulated prosthetic vision by operating a game controller that simulates the subject's movement. The prosthetic vision was simulated as the image taken by a body-mounted camera (Fig. 1). Wayfinding performance was measured by the time the subject took to traverse the maze and the number of errors made during travel. It was found that background noise did not significantly interfere with task performance. However, performance deteriorated with phosphene dropout. Subjects' task performance improved through practice.

In that study the pixelized image was not anchored to a particular retinal location, and consequently, the image could be scanned using eye movements. We refer to such a simulation of prosthetic vision as *free viewing*, which is different from the technology currently under clinical testing.^{2, 3, 17} In the current technology, an electrode array is fixed at a certain retinal location. Consequently, the pixelized image, captured by a head/body-mounted camera, is always viewed through the same retinal area and does not respond to a shift in eye position unless special provisions such as eye tracking are built into the system. We refer to the simulation of such prosthetic vision as *gaze-locked viewing*. Though our research established that vision provided by a low-resolution retinal prosthesis could be useful for wayfinding in certain environments when using free viewing, it is yet to be known whether this would still be the case for gaze-locked viewing. In the present study, we investigated wayfinding performance using gaze-locked viewing under conditions otherwise similar to those in our previous study.¹⁰

METHODS

Subjects

Four subjects (Ss) (2 males and 2 females), who had 20/30 or better visual acuity with no or best correction and were between 20 and 50 years of age, participated in the present study. Ss had participated in our previous study and had extensive experience with the performance of the maze navigation task in the free viewing condition. They were therefore familiar with the pixelized image and the maze navigation task.

The study was designed in accordance with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of the Johns Hopkins University School of Medicine. Informed consent was obtained from each S after explanation of the nature and possible consequences of the study. Ss received a lunch coupon and 10 USD for each one-hour test session.

Retinal Prosthesis Simulation

Prosthetic vision was simulated in a monocular video visor as a grid of 6×10 phosphenes, visible only to the left eye. The phosphene grid spanned 27° × 16.2°. Each phosphene had a circular Gaussian luminance profile against a dark background with a standard deviation of 0.7° (Fig. 2-A). Pixel luminance ranged from 0 (darkest) to 255 (brightest). Peak luminance of any phosphene was obtained as follows:

$$\text{Peak luminance} = (\text{LSL}/\text{MSL}) \times \text{PLR} + \text{PBL}$$

Where LSL is the mean luminance across the scene area subtended by the phosphene, MSL is the maximum luminance in the scene, PLR is the phosphene luminance range, and PBL is the phosphene background luminance.

Three parameters were manipulated: Rayleigh luminance contrast (Contrast) defined as $PLR / (PLR + PBL)$, background noise (Noise), and phosphene dropout (Dropout). Based on observations of brightness resolution in a clinical study,³ we chose a phosphene luminance scale of 8 gray levels. Background noise was created by adding randomly-scattered “sparks” to the pixelized image (Fig. 2-B) such that five bright dots were added into each video frame and then began to fade in brightness with an exponential decay and a half life of 10 video frames, simulating the photopsias often reported by patients with retinal blindness. Phosphene dropout was created by randomly selecting 30% of the phosphenes in the pixelized image (Fig. 2-C) and setting their brightness to the PBL level, simulating the condition of a retinal prosthesis with some malfunctioning electrodes and/or unresponsive patches of retina. Fig. 2-D shows a simulation combining background noise and phosphene dropout. A pupil-imaging camera and infrared illumination built into the visor in conjunction with ViewPoint eye tracking software (Arrington Research Inc, Scottsdale, AZ) allowed tracking gaze position at 30 Hz. One concern about eye tracking at 30 Hz was that it might delay updating of the eye position during large saccades, causing the image that was projected on the retina to “slip.” We monitored saccade occurrence during task performance and observed few large saccades. We thus concluded that the phosphene grid was effectively gaze-locked on the retina during the experiment. Though the precision of this gaze-locking fell short of stabilized vision in both space and time, the spatial precision was well within the size of an electrode and therefore the net result was that subjects kept their gaze steady within a 1° window. The retinal prosthesis was simulated as being implanted over the macula. Ss navigated scenes in pixelized imagery by operating a game controller simulating the S's movement with a body-mounted camera.

Virtual Maze

The virtual mazes used in the present study were the same as those in our previous study.¹⁰ The ten 10-room mazes, each having a different floor plan, were simulated in virtual reality using Worldcraft freeware (<http://www.fileplanet.com/>) and could be traversed using a game controller and the HalfLife gaming engine (Valve Corporation, Bellevue, WA). The rooms were empty and numerically labeled on one of the walls with 1 (Entrance) through 10 (Exit) as shown in Fig. 3. Room labels were not visible from outside of the room. The only correct route was to traverse the maze through Room 1 to 10 in order. The maze was shown to Ss only as a pixelized image. Fig. 4 shows a portion of the scene of Fig. 3 in pixelized form.

Experimental Design and Procedure

Maze navigation performance was measured with two variables: Time (in seconds) the subject took to traverse a maze (*Time*) and number of errors the subject made during the trip (*Errors*). An error was defined as the subject's return to a previous room. A *trial* was defined as a complete trip navigating from Room 1 to Room 10.

The experiment was designed to assess maze navigation performance using gaze-locked viewing under 5 conditions. Effects of Contrast, Noise, and Dropout were investigated and described in detail in the Results section. The experiment was divided into 5 blocks as shown in Table 1. Each block had one distinct experimental condition. The block order was arranged to be consistent with that in our previous study.¹⁰ All Ss participated in all 5 blocks in the same order.

Subjects were tested in a one-hour session per week, performing as many trials as time permitted. No two consecutive trials used the same maze. For each trial, the subject was instructed to traverse Room 1 through Room 10 in minimum time.

Data Collection and Analysis

Time was recorded by the experimenter using a stop watch and *Errors* through observation. To reduce heteroscedasticity, a logarithmic transformation was applied to *Time* and a square-root transformation to *Errors* for statistical analysis. Transformed data were analyzed using SAS (SAS institute Inc, Cary, NC) as described in the Results section.

Results

Relationship between Performance Time and Errors

We first examined the *correlation* between $\log(\text{Time})$ and $\sqrt{\text{Errors}}$ across all conditions. It was found that $\log(\text{Time})$ and $\sqrt{\text{Errors}}$ were positively correlated, with *Pearson correlation coefficient* ranging from 0.72 to 0.84 across Ss (Table 2). Because of this high correlation between $\log(\text{Time})$ and $\sqrt{\text{Errors}}$, we will present only timing results, as $\log(\text{Time})$. Results for $\sqrt{\text{Errors}}$ were statistically equivalent to those for $\log(\text{Time})$.

Adaptation to Gaze-locked Viewing

Ss first performed the maze navigation in gaze-locked viewing under the condition of high contrast, no noise, and no dropout (Block 1). Block 1 was designed to have 20 trials, with the first half of Block 1 serving as practice for Ss to adapt to the gaze-locked viewing condition. Three subjects, S12, S31, S20, performed all 20 trials. Linear regression of $\log(\text{Time})$ on trial for the second half of Block 1 revealed that the slope of the regression line for each of the three subjects was not significantly different from 0, showing that task performance was close to an asymptote after about 10 trials. After S23 had performed 11 trials in Block 1, we found that S23 showed similar performance stability in trials 6-11 as the other subjects in trials 11-20 (Table 3, columns under Second Half). We therefore decided to include S23's abbreviated data in the analysis. To examine performance improvement in the first half of Block 1, we conducted the linear regression of $\log(\text{Time})$ on trial for the first half of Block 1, and found that the slopes of the linear regression for all subjects were negative but not significantly different from zero (Table 3, columns under First Half). We then conducted a one-way (2) *repeated measures analysis of variance* on $\log(\text{Time})$, to examine if there was a substantial decrease in mean $\log(\text{Time})$ from the first half of Block 1 to the second half. The result showed that, across all subjects, the mean $\log(\text{Time})$ in the second half was significantly less than that in the first half ($F(1, 3) = 12.47, p < 0.05$). Fig. 5 shows the mean and standard deviation of $\log(\text{Time})$ in the first and second half of Block 1 for each S. In order for the reader to have an appreciation of the adaptation process, Fig. 6 shows both *Time* (Panel A) and $\log(\text{Time})$ (Panel B) as a function of trial number in Block 1.

In between Block 1 and 2, Ss were given 8-9 practice trials using low contrast. We examined $\log(\text{Time})$ in blocks 2-5 for evidence of performance improvement over trials by performing the linear regression of $\log(\text{Time})$ on trial number within each block. As shown in Table 4, no slopes of the linear regression were found to be significantly different from zero in any block for any S. We therefore concluded that Ss' adaptation to gaze-locked viewing was essentially complete by the end of Block 1.

Contrast, Noise, and Dropout Effects

Data in the second half of Block 1 (high contrast) and data collected in Block 2 (low contrast) were analyzed to assess the effect of Contrast on task performance. Ss performed the task for

12-13 trials in Block 2 (see Table 1). We conducted a one-way (2) *repeated measures analysis of variance* on log(Time). Contrast had two levels, high (68%) vs. low (16%) contrast. The analysis revealed no significant difference in mean log(Time) between the two contrast levels ($F(1, 3) = 0.09, p > 0.05$). However, the variation, i.e., standard deviation of log(Time), was greater in the condition of low contrast across all subjects (Table 5).

The effects of Noise and Dropout on task performance were assessed at low contrast. Data collected in Blocks 2-5 were subject to the analysis. Ss performed the task for 10-13 trials in Blocks 3-5. We conducted a two-way (2x2) *repeated measures analysis of variance* on log(Time) to assess effects of Noise, Dropout, and interaction between Noise and Dropout. We found a main effect of Dropout on log(Time) ($F(1, 3) = 16.16, p < 0.05$), but no significant effect of Noise ($F(1, 3) = 2.28, p > 0.05$) or interaction between Dropout and Noise ($F(1, 3) = 0.23, p > 0.05$). Fig. 7 shows mean log(Time) as a function of Noise and Dropout for each subject.

Discussion

Our results demonstrate that virtual maze navigation can be performed with simulated prosthetic vision in gaze-locked viewing, suggesting that a 6x10 electrode retinal prosthesis with low spatial resolution may be useful for certain wayfinding tasks, for example, identifying landmarks from a distance which cannot be performed with other mobility aids such as a cane. Mobility maneuvers involving obstacle detection, such as walking up and down the stairs, are unlikely to benefit from the low-level vision presented to our subjects. However, the combination of such a device with traditional mobility aids may confer appreciable benefits to a functionally sightless individual.

In the present study, we manipulated three variables; luminance contrast, background noise, and phosphene dropout. Those three variables are all associated with the retinal condition and device parameters with which a retinal prosthesis wearer has to contend. Our finding that phosphene dropout could have a major impact on wayfinding. On average, a dropout of 30% of the phosphenes increased performance time by about 40%. However, wayfinding was not significantly affected by noise, at least after adequate practice. Our findings are in agreement with our previous observations under free-viewing conditions.¹⁰ Taken together, these results suggest that human vision is capable of adapting to visual conditions resembling the degenerating retina. On the other hand, the configurations of phosphene grids in our study are a simplification of what a prosthesis wearer may experience. For example, the wearer might perceive phosphenes of various sizes and shapes, in a layout less regular than the spatial configuration of the electrode array. The magnitude of such variations and distortions is yet to be known once data from implant wearers become available. In addition, further changes in the patient's vision condition may occur after a retinal prosthesis is implanted. Technical adjustment of the device and the wearer's adaptation to new conditions may be needed throughout the life span of the implant. Prospective retinal prosthesis wearers are likely to be up to such challenges because they have experienced gradual and progressive vision loss and such experiences may help them better adapt to new visual conditions than our normally sighted subjects.

The virtual maze used in this experiment was intended to be a tool for evaluation of functional vision using a simulated retinal prosthesis. It represents a greatly simplified environment that may be rarely seen in real life. Future prosthesis wearers would have to deal with far more complex environments than this virtual maze. The present study can be seen as the first step toward comprehensive simulation of real-life environments. In future research, one can explore effective approaches to transferring prosthesis wearers' mobility skills from simpler to more complex environments.

Performance improvement through practice has been reported in several studies of simulated prosthetic vision.^{10, 18-23} In our experiment, rapid adaptation to a new viewing condition was observed. This may be attributed to Ss' prior experience with both simulated prosthetic vision and virtual maze navigation. It may take longer for a naïve normally-sighted subject to adapt to a viewing condition with this degree of difficulty. Therefore, our results on adaptation may have limited relevance to scenarios more complex than that in the present study. All Ss performed the maze navigation task in the same order of conditions (Table 1). We examined the possible effects of practice over the trials within each condition and did not find significant practice effects. However, the design of the study does not allow us to tease apart order and practice effects across experimental conditions from the effects of interest. This issue can only be addressed with an experimental design of counter-balanced conditions.

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REFERENCES

- Humayun MS, de Juan E Jr, Dagnelie G, Greenberg RJ, Propst RH, Phillips DH. Visual perception elicited by electrical stimulation of retina in blind humans. *Arch Ophthalmol* 1996;114:40–6. [PubMed: 8540849]
- Zrenner E. Will retinal implants restore vision? *Science* 2002;295:1022–5. [PubMed: 11834821]
- Humayun MS, Weiland JD, Fujii GY, Greenberg R, Williamson R, Little J, Mech B, Cimmarrusti V, Van Boemel G, Dagnelie G, de Juan E. Visual perception in a blind subject with a chronic microelectronic retinal prosthesis. *Vision Res* 2003;43:2573–81. [PubMed: 13129543]
- Mahadevappa M, Weiland JD, Yanai D, Fine I, Greenberg RJ, Humayun MS. Perceptual thresholds and electrode impedance in three retinal prosthesis subjects. *IEEE Trans Neural Syst Rehabil Eng* 2005;13:201–6. [PubMed: 16003900]
- Dagnelie G. Visual prosthetics 2006: assessment and expectations. *Expert Rev Med Devices* 2006;3:315–25. [PubMed: 16681453]
- Wilke R, Kutenkeuler C, Wilhelm B, Sailer H, Sachs H, Gabel V-P, Besch D, Bartz-Schmidt K, Zrenner E. Subretinal chronic multi-electrode arrays in blind patients: perception of dots and patterns. *Invest Ophthalmol Vis Sci* 2006;47E-Abstract 3202
- Cha K, Horch KW, Normann RA. Mobility performance with a pixelized vision system. *Vision Res* 1992;32:1367–72. [PubMed: 1455709]
- Perez Fornos A, Sommerhalder J, Chanderli K, Pittard A, Baumberger B, Flückiger M, Safran AB, Pelizzone M. Minimum requirements for mobility in known environments and perceptual learning of this task in eccentric vision. *Invest Ophthalmol Vis Sci* 2004;45E-Abstract 5445
- Sommerhalder JR, Perez Fornos A, Chanderli K, Colin L, Schaer X, Mauler F, Safran AB, Pelizzone M. Minimum requirements for mobility in unpredictable environments. *Invest Ophthalmol Vis Sci* 2006;47E-Abstract 3204
- Dagnelie G, Keane P, Narla V, Yang L, Weiland J, Humayun M. Real and virtual mobility performance in simulated prosthetic vision. *J Neural Eng* 2007;4:S92–101. [PubMed: 17325421]
- Hetling JR, Baig-Silva MS. Neural prostheses for vision: designing a functional interface with retinal neurons. *Neurol Res* 2004;26:21–34. [PubMed: 14977054]
- Rizzo JF 3rd, Wyatt J, Loewenstein J, Kelly S, Shire D. Perceptual efficacy of electrical stimulation of human retina with a microelectrode array during short-term surgical trials. *Invest Ophthalmol Vis Sci* 2003;44:5362–9. [PubMed: 14638739]
- Weiland JD, Humayun MS, Dagnelie G, de Juan E Jr, Greenberg RJ, Iliff NT. Understanding the origin of visual percepts elicited by electrical stimulation of the human retina. *Graefes Arch Clin Exp Ophthalmol* 1999;237:1007–13. [PubMed: 10654170]

14. Rizzo JF 3rd, Wyatt J, Loewenstein J, Kelly S, Shire D. Methods and perceptual thresholds for short-term electrical stimulation of human retina with microelectrode arrays. *Invest Ophthalmol Vis Sci* 2003;44:5355–61. [PubMed: 14638738]
15. Jones BW, Marc RE. Retinal remodeling during retinal degeneration. *Exp Eye Res* 2005;81:123–37. [PubMed: 15916760]
16. Heckenlively JR, Yoser SL, Friedman LH, Oversier JJ. Clinical findings and common symptoms in retinitis pigmentosa. *Am J Ophthalmol* 1988;105:504–11. [PubMed: 3259404]
17. Sachs HG, Gabel VP. Retinal replacement—the development of microelectronic retinal prostheses—experience with subretinal implants and new aspects. *Graefes Arch Clin Exp Ophthalmol* 2004;42:717–23. [PubMed: 15309557]
18. Sommerhalder J, Oueghlani E, Bagnoud M, Leonards U, Safran AB, Pelizzone M. Simulation of artificial vision: I. Eccentric reading of isolated words, and perceptual learning. *Vision Res* 2003;43:269–83. [PubMed: 12535986]
19. Dagnelie G, Barnett D, Humayun MS, Thompson RW Jr. Paragraph text reading using a pixelized prosthetic vision simulator: parameter dependence and task learning in free-viewing conditions. *Invest Ophthalmol Vis Sci* 2006;47:1241–50. [PubMed: 16505065]
20. Thompson RW Jr, Barnett GD, Humayun MS, Dagnelie G. Facial recognition using simulated prosthetic pixelized vision. *Invest Ophthalmol Vis Sci* 2003;44:5035–42. [PubMed: 14578432]
21. Hayes JS, Yin VT, Piyathaisere D, Weiland JD, Humayun MS, Dagnelie G. Visually guided performance of simple tasks using simulated prosthetic vision. *Artif Organs* 2003;27:1016–28. [PubMed: 14616520]
22. Dagnelie G, Walter M, Yang L. Playing checkers: Detection and eye-hand coordination in simulated prosthetic vision. *J Modern Optics* 2006;53:1325–42.
23. Chen SC, Hallum LE, Lovell NH, Suening GJ. Learning prosthetic vision: a virtual-reality study. *IEEE Trans Neural Syst Rehabil Eng* 2005;13:249–55. [PubMed: 16200748]

Figure 1. Video headset through which pixelized scene as shown in the computer monitor (in background) was seen. A color version of this figure is available online at www.optvissci.com.

Figure 2.

Pixelized image with (A) no background noise and 0% phosphene dropout, (B) background noise and 0% phosphene dropout, (C) no background noise and 30% phosphene dropout, and (D) background noise and 30% phosphene dropout.

Room 1 **Room 10**

Figure 3.
The entrance (Room 1) and exit (Room 10) in the virtual maze.

Figure 4.
Portions of room images from Fig. 3 seen through the simulated phosphene array.

Figure 5. Mean log(Time) of maze navigation performance in the first and second half of Block 1 for each S. The error bar represents standard deviation.

Figure 6. Maze navigation performance across trials in Block 1 for each S. Values along the ordinate are shown in Panel A as Time, in Panel B as $\log(\text{Time})$.

Figure 7. Mean log(Time) of maze navigation performance under conditions of low contrast combined with noise and/or dropout. Error bars represent standard deviation.

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Table 1

The Experimental Execution Plan.

Block #	Condition			Number of Trials				
	Contrast	Noise	Dropout	S12	S31	S23	S20	
1	High	No	No	20	20	11	20	
2	Low	No	No	12	13	12	12	
3	Low	Yes	No	10	12	12	12	
4	Low	No	Yes	12	12	12	12	
5	Low	Yes	Yes	10	12	12	12	

Table 2Correlation (r) between log(Time) and sqrt(Errors).

Subject	r	n
S20	0.77	60
S31	0.72	61
S23	0.84	51
S12	0.73	58

Table 3Linear Regression of $\log(\text{Time})$ on Trial over the First and Second Half of Block 1.

Subject	First Half		Second Half	
	$\log(\text{Time}) = \log(T_0) + m \cdot \text{Trial}$	$H_0: m = 0$	$\log(\text{Time}) = \log(T_0) + m \cdot \text{Trial}$	$H_0: m = 0$
S12	$3.07 - 0.019 \cdot \text{Trial}$	$t = -1.07, p > 0.05$	$3.15 - 0.025 \cdot \text{Trial}$	$t = -1.50, p > 0.05$
S31	$2.67 - 0.027 \cdot \text{Trial}$	$t = -1.02, p > 0.05$	$2.50 - 0.010 \cdot \text{Trial}$	$t = -1.13, p > 0.05$
S23	$3.41 - 0.095 \cdot \text{Trial}$	$t = -1.61, p > 0.05$	$3.00 - 0.042 \cdot \text{Trial}$	$t = -2.22, p > 0.05$
S20	$2.84 - 0.013 \cdot \text{Trial}$	$t = -0.48, p > 0.05$	$2.50 + 0.007 \cdot \text{Trial}$	$t = 0.39, p > 0.05$

Table 4

Slopes of Linear Regression of log(Time) on Trial in Condition Combinations of Low Contrast with Noise and Dropout.

Subject	No noise No dropout	Noise No dropout	No noise Dropout	Noise Dropout
S12	$m = -0.004$ $t = -0.13, p > 0.05$	$m = 0.011$ $t = 0.37, p > 0.05$	$m = -0.035$ $t = -1.30, p > 0.05$	$m = -0.035$ $t = -1.24, p > 0.05$
S31	$m = 0.019$ $t = 1.13, p > 0.05$	$m = 0.009$ $t = 0.39, p > 0.05$	$m = 0.011$ $t = 0.53, p > 0.05$	$m = 0.011$ $t = 0.64, p > 0.05$
S23	$m = 0.022$ $t = 1.09, p > 0.05$	$m = 0.017$ $t = 0.71, p > 0.05$	$m = 0.003$ $t = 0.13, p > 0.05$	$m = 0.001$ $t = -0.07, p > 0.05$
S20	$m = -0.017$ $t = -0.58, p > 0.05$	$m = 0.006$ $t = 0.32, p > 0.05$	$m = 0.016$ $t = 0.84, p > 0.05$	$m = -0.011$ $t = -0.59, p > 0.05$

The linear regression equation is $\log(\text{Time}) = \log(T_0) + m \cdot \text{Trial}$, with the null hypothesis $H_0: m = 0$.

Table 5

Mean log(Time) in High and Low Contrast Conditions.

Subject	High Contrast		Low Contrast	
	Log(Time)	CV (%)	Log(Time)	CV (%)
S12	2.76±0.15	5.49	2.79±0.22	7.91
S31	2.36±0.09	3.74	2.58±0.16	6.10
S23	2.62±0.08	2.88	2.53±0.18	7.26
S20	2.60±0.15	5.81	2.53±0.22	8.74

The format for the column log(Time) is mean ± standard deviation.

CV stands for coefficient of variation and is defined as (standard deviation / mean log(Time)) × 100.