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Auditory Localization Performance with Asymmetric Integrated Eye and Ear Protection

by Angelique A Scharine, Morgan Domanico, Ashley N Foots, Kim Fluitt, and Timothy J Mermagen

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14. ABSTRACT

The effect of the Asymmetric Integrated Eye and Ear Protection (AIEEP) prototype on auditory localization ability was measured for 6 participants wearing 1 of 2 sample prototypes. The AIEEP is a tactical communications and protection system (TCAPS) that also provides eye protection. Participants used a laser pointer to indicate the perceived location of sounds presented from 1 of 36 loudspeakers. This task was completed both with ears unoccluded (no AIEEP) and with the AIEEP. Pink noise bursts were used for the sound stimuli (either 250 or 7000 ms). Localization accuracy was computed as the horizontal angular difference between the target loudspeaker location and the participant's estimate. Responses were classified as to whether they constituted correct answers, minor errors due to blur, or front-back reversals. Because there were significant differences in performance as a function of the prototype used, the data are reported separately. Although decreased acuity and increased reversals were observed relative to performance with the bare head, performance with Prototype B was similar to that of the earlier prototype, the Gamma-IEEP, and better than that measured for another in-the-ear TCAPS. Performance with Prototype A was significantly worse, suggesting that issues with the sample were affecting localization.

15. SUBJECT TERMS

auditory localization, TCAPS, hearing protection, eye protection, auditory situation awareness

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1. Introduction

This effort was funded by the US Army Natick Soldier Research, Development and Engineering Center's (NSRDEC's) Warfighter Directorate. The objective was to measure the effect of the use of a prototype device designed to provide Soldiers with integrated eye and ear protection on auditory localization performance.

1.1 Asymmetric Integrated Eye and Ear Protection (AIEEP)

The Asymmetric Integrated Eye and Ear Protection (AIEEP, Fig. 1) was manufactured for NSRDEC by Applied Research Associates, Inc. (ARA) and Revision Military Technologies under contract W911QY-16-C-0004. The AIEEP combines ARA's hybrid hearing protection technology with Revision Military's ballistic eye protection and distortion-free vision. The hearing protection portion of this technology provides passive sound attenuation capabilities and electronic limiters that suppress transmission of impulsive and high-level steady-state noise. In addition, the manufacturer indicates that the system's active pass-through microphone technology restores normal levels of hearing when ambient noise levels are below 85 dBA.[*] Asymmetric refers to the fact that the electronics are integrated across the entire spectacle frame (instead of having individually operated left and right sides like the previous versions). AIEEP has 3 modes of operation: the high mode, which maintains normal hearing levels (unity gain) while providing protection from impulsive noise; the low mode for use in continuous noise environments (20-dB sound attenuation plus impulse protection); and the passive mode (off), which provides attenuation of both continuous and impulsive noise. The high mode is the only mode intended to offer normal ambient auditory awareness, and therefore testing was conducted with the system active in the high mode.

[*] Decibels "A-weighted" is the sound pressure level adjusted for the sensitivity of the average human ear. The reference level is the loudness of a 1000-Hz tone presented at 40-dB sound pressure level. Humans are less sensitive to low frequencies and more sensitive to frequencies between 1 and 10 kHz.

Fig. 1 **AIEEP device with clear ballistic lens and comply foam earphone tips**

1.2 Auditory Localization

Human listeners localize sounds using several spatial cues derived from the sound wave arriving at their ears: binaural, monaural, and movement-based. Binaural cues are the result of differences in arrival time and sound pressure level between the 2 ears, providing information about the right/left position of a sound source. Monaural cues are created as the sound reflects off parts of the body and these reflections add into the original sound wave. Monaural cues give information about a sound source's elevation and placement along the front–back axis. Movement of the head provides multiple sets of binaural cues, which in combination with information about the head's movement reduces ambiguity in these binaural cues and increase accuracy of localization estimates.

Auditory localization errors stem from failure to fully resolve binaural and monaural cues. Localization errors due to limitations in acuity are called localization blur, and this underlying variability is due to our limited ability to resolve binaural information. Humans can only localize horizontally within a certain range of error (Oldfield and Parker 1984).

Binaural cues only specify a ring of potential locations that all share the same interaural time and intensity differences. This ring is known as the "cone of confusion" (Fig. 2). Monaural cues resolve this ambiguity, but they are vulnerable to distortion and masking. Monaural cues are the result of individualized spectral changes that are dependent on the individual's profile, and as such they are easily altered by the use of headgear.

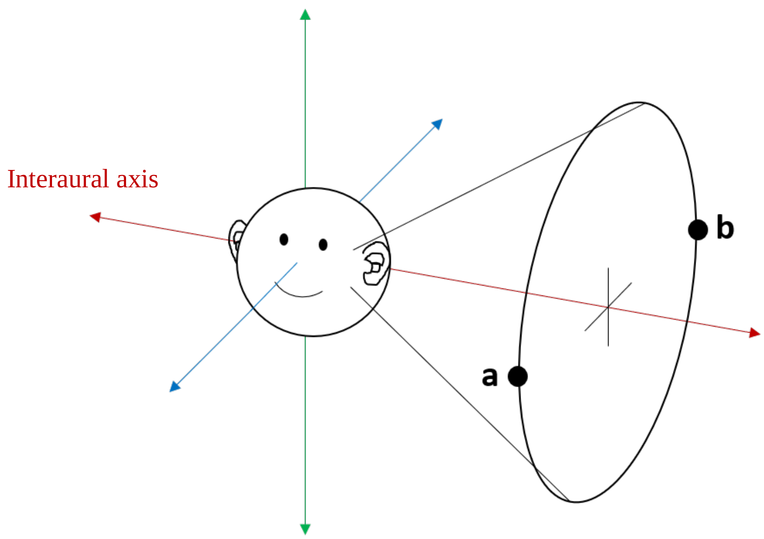

Fig. 2 **Schematic representation of the "cone of confusion", described as the set of locations sharing the same set of binaural difference cues**

Failure to resolve this ambiguity manifests itself in errors that result from choosing another location within the cone of confusion that has similar binaural information but different monaural information. Thus, if the potential response set is limited to the horizontal axis, the error for location "a" in Fig. 2 results in choosing location "b", which is located in the same right/left position but mirrored about the interaural axis in the reverse hemisphere. In practice, these ambiguities can also be resolved by movements of the head and visual confirmation (Wallach 1940). However, as these are not always available, the use of headgear is a potential source of auditory spatial ambiguity that is to be mitigated to the extent possible.

Localization ability measured for brief signals represents the "worst case scenario", because the listener is forced to use only monaural cues to disambiguate the binaural cues. If sounds are long enough to allow the listener to move his or her head, the movement can provide them with multiple "samples" of auditory spatial information, greatly reducing the ambiguity (Wallach 1940; Thurlow et al. 1967). As such, localization ability measured for longer stimuli provides information about the upper boundary of individual localization ability.

1.3 Localization with Hearing Protection and Other Headgear

Hearing protection devices (HPDs), Tactical Communications and Protection Systems (TCAPS), and other forms of headgear have been shown to alter the perception of monaural cues, resulting in both increased localization blur and front–back confusions. Previous research has shown that helmets can increase unsigned localization errors on average as much as 13° (Scharine and Weatherless 2014). Scharine and Weatherless (2014) measured increases to average unsigned localization error of approximately 18° for passive, level-dependent earplug style HPDs. Similar increases were measured for active earplug (~20°) and earmuff (~25°) style TCAPS (Scharine and Weatherless 2013). In both cases, increases in front–back confusions near 0° and 180° were observed. These well-documented effects have led to the inclusion of auditory localization ability as a measure of auditory "situation awareness" for TCAPS, and it has been included as an element of the requirements drafted during the acquisition of Soldier equipment.

1.4 Standardization of Localization Measurement

There are ongoing efforts to develop an American National Standards Institute (ANSI)/Acoustical Society of America (ASA) standard for measurement of auditory localization ability with head-borne equipment. The AIEEP was tested according to the proposed Method 2, as specified in the following section.

1.5 Auditory Localization Measurement (ANSI/ASA Proposed Method 2)

1.5.1 Loudspeaker Array

Method 2 was developed to fully characterize the auditory spatial performance of listeners, either for research purposes or after down-selecting items tested with Method 1. Method 2 requires a hemi-anechoic facility, a horizontal array of 36 evenly spaced loudspeakers, and a position tracker that allows the listener to respond to the full 360° horizontal range.

1.5.2 Stimulus Duration

Method 2 prescribes the use of target stimuli with 2 durations: short (250 ms) and long (7000 ms). The intent is to capture localization performance as a function of real-world variability in sound event duration (Vliegen and Van Opstal 2004; Bernhard 2015). Performance, as measured for the short and long stimuli, characterizes the range of localization ability demonstrated in the real world. Statistically, more trials are needed for the short-duration stimuli due to greater variability in localization for these stimuli. In contrast, fewer presentations are required for the long-duration stimuli, as listeners are able to be both consistent and accurate. To obtain reliable measurements in the minimum testing time, twice as many short stimuli are presented as long stimuli. For each block of testing, 72 short stimuli and 36 long stimuli were presented.

While there is no established performance criterion for auditory localization performance with TCAPS, we can compare the data obtained with the proposed ANSI/ASA method with those obtained for the bare head and other devices. Auditory localization performance was previously measured for listeners wearing a previous prototype of the Gamma-Integrated Eye and Ear Protection, known as the Gamma-IEEP (Scharine et al. 2016). This device was similar in appearance to the current prototype, the differences are mainly in the way the electronics are embedded in the frames of the device. For 250-ms stimuli, mean unsigned error increased by 3° when wearing the Gamma-IEEP (mean error: ~13°) versus bare-headed performance (mean error: ~10°). An increase in mean unsigned error of only 3° is relatively small; for example, we measured an increase in mean unsigned error of 20° for another in-the-ear HPD (Scharine and Weatherless 2014). To the extent that the electronics do not alter the signal significantly from that experienced with the previous prototype, we expect similar performance for this new prototype.

2. Method

2.1 Participants

Six participants participated in the testing. Testing criteria required that participants be age 18 or older and have normal hearing. Normal hearing was defined as bilateral hearing thresholds no greater than 25 dB HL* at all audiometric frequencies from 250 to 8 kHz, including 3 and 6 kHz. Further, bilateral threshold differences were not greater than 10 dB at any given frequency. Prior to testing, participants' ear canals were visually inspected with an otoscope to ensure normal morphology and the absence of cerumen and debris that might prevent the insertion of earphone tips.

2.2 Test Facility

The study was conducted in the Dome Room of the Environment for Auditory Research at Aberdeen Proving Ground, a large sound-treated room instrumented with a horizontal array of 180 loudspeakers positioned at 2° increments (Henry et al. 2009). Thirty-six of the 180 loudspeakers were used in accordance with Method 2: the participant was oriented so that the active loudspeakers start at 5°, and there are 36 loudspeakers at 10° increments from 5° to 355° (Fig. 3).

* Decibels hearing level (dB HL) is the sound pressure level, in decibels, relative to the average human threshold level.

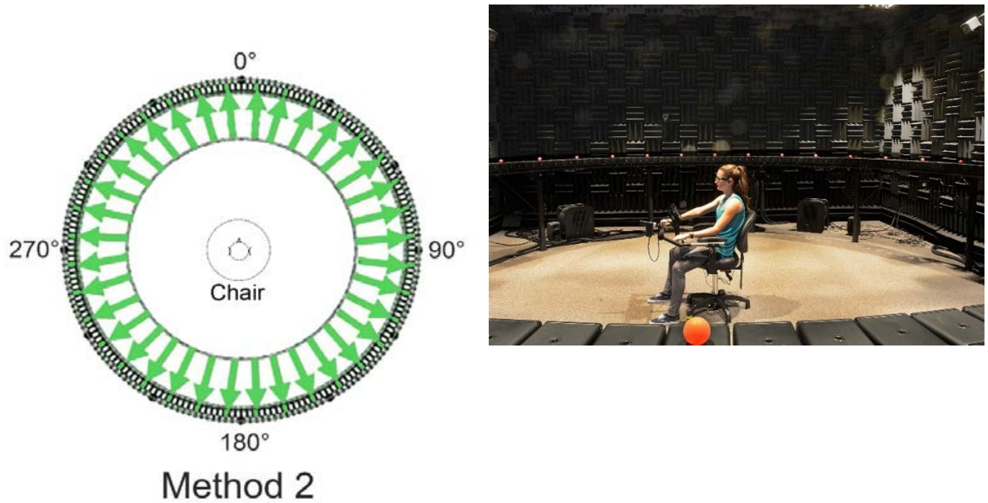

Fig. 3 Loudspeaker configuration in the dome room. Method 2 testing incorporates 36 loudspeakers spaced at even intervals of 10°, beginning at 5° and continuing to 355°.

All sound presentation was controlled using a custom MATLAB R2014b (Mathworks 2014) script running on a computer operating Windows 7 and located in a separate control room. Research participants were seated in a rotating chair instrumented with a tracking system. Participants responded by rotating the chair and pointing a laser pointer at the perceived source location. The tracking system's response coordinates were recorded by the control room computer.

2.3 Localization Test

2.3.1 Target Stimuli

The target stimulus was a randomly generated pink broadband (200 Hz to 14 kHz) noise signal, edited to 1 of 2 stimulus durations, short (250 ms) and long (7000 ms) with 10-ms cosine onset and offset ramps. To avoid the use of level as a source of localization information, stimulus level was randomly over 3 levels (65, 70, and 75 dBA).

Two types of 7000-ms stimuli were used: pulsed (250-ms on/off cycle) and steady. The previous test of the Gamma-IEEP (Scharine et al. 2016) used steady-state signals for the 7000-ms sounds. The current proposed standard changed this to a pulsed signal because some newer electronic devices use digital signal processing that filters sound based on the directionality of the signal onset. If the listener moves during the steady signal, the dynamic relationship of the listener to the source is changing, but the electronic device would continue to filter a steady signal based on the initial onset directionality of the sound. A pulsed signal will have multiple onsets, reducing the probability of this occurring. The current device under test does not use this type of signal processing; therefore, the signal type should not matter.

To remain consistent with the latest version of the standard, while ensuring that any differences in performance on the AIEEP relative to the Gamma-IEEP were not due to differences in the signal used, we chose to include both steady and pulse signals in the 7000-ms trials.

2.3.2 AIEEP Earphone Tip Fitting

A Comply Canal Tips Fitting Guide* measurement tool was used to identify the proper-sized earphone tips for each participant. Participants were then instructed on proper insertion of the earphone tips and asked to practice inserting them until they felt comfortable doing so. The experimenter verified that the earphone tips were placed so as to be fully inserted in the ear canal but did not assist with insertion after training.

2.3.3 Stimulus Blocks

Task: The participant was seated in an instrumented chair placed in the center of the loudspeaker array (Fig. 3). After initiating a trial, a sound is presented from one of the loudspeakers in the array. The participant then rotated the chair to point the laser mounted on the chair at the perceived sound source and pressed a button to indicate the perceived sound source location. The participant began each trial facing the 0° position. Participants were free to move during the sound presentation; however, the 250-ms trials were too brief for the participant to move much during the sound's presentation. During the 7000-ms trials, movement was encouraged, and the trial did not end until the participant responded.

Training: A block of trials consisted of 3 trials (two 250-ms trials and one 7000-ms trial) presented from each of 10 test locations for a total of 30 trials randomly selected for each participant from the locations to be used in the test. The order of trials (duration and location) was random. Participants completed 5 training blocks.

The loudspeakers were marked during training by placing a pink ping-pong ball in a divot centered on the top of the loudspeaker. Participants were not provided with feedback during training or testing, so these markers were used to teach the listeners where the potential source locations would be and to increase the probability of reliable performance. During testing, these markers were removed to reduce the interaction of visual information with auditory spatial cues.

Testing: A block of trials consisted of 3 trials (two 250-ms trials and one 7000-ms trial) from each of the 36 locations. Each block, therefore, had 72 short and 36 long trials. Participants completed a total of 8 blocks of trials, 4 blocks with the ears

* Comply canal tips are manufactured by SELEX Communications, Basildon, UK.

unoccluded (no AIEEP) followed by 4 blocks with the AIEEP. Half of the blocks, 2 with the AIEEP and 2 without, used the pulsed 7000-ms stimulus instead of the steady stimulus. The training and test blocks are summarized for reference in Table 1.

Table 1 Blocks and test conditions

Block	TCAPS	Trials	Stimuli (long)
T1	None	30	Steady
T2	None	30	Steady
T3	None	30	Steady
T4	None	30	Steady
T5	None	30	Steady
1	None	108	Pulsed
2	None	108	Pulsed
3	None	108	Steady
4	None	108	Steady
5	AIEEP	108	Pulsed
6	AIEEP	108	Pulsed
7	AIEEP	108	Steady
8	AIEEP	108	Steady

Since variability in performance is often observed as a function of the fit of in-the-ear devices, the AIEEP was refitted after 2 blocks of testing. In addition, 2 AIEEP prototypes were provided for testing. To account for variability between devices, 3 participants wore Prototype A and 3 wore Prototype B.

3. Results

3.1 Dependent Variables

Signed (bias) angular difference between the source location and the location of the loudspeaker nearest the response location. Appendix A gives a description of the formulas used to compute these.

Unsigned (magnitude) angular difference between the source location and the location of the loudspeaker nearest the response location.

Each response was also classified according to whether the answer was one of the following:

1) “Correct”: within 5° of the target loudspeaker

2) “Blurred”: not correct but within 15° of the correct loudspeaker

3) “Reversal”: within 15° of the matching loudspeaker in the opposite hemisphere (front/back). Section 3.7 further describes computation of reversals.

3.2 Prototype Differences

While wearing Prototype A, one participant noted that the 7000-ms signal seemed to emanate from 2 locations: “the higher frequencies seem offset from the lower frequencies by about 30° to the left of the source”. This participant ran the same blocks with Prototype B and reported a similar effect, but that the offset was less obvious, approximately 15°. The participant only noted this issue for the long stimuli.

This was reported to ARA, but personnel were unable to duplicate the effect in their laboratory. Therefore, both prototypes were included in testing. Although no other participants reported any issues, prior to conducting further analyses we compared performance as a function of prototype. Fig. 4 shows mean unsigned error as a function of prototype used, AIEEP use and stimulus duration. There are obvious differences in performance between the 2 prototypes.

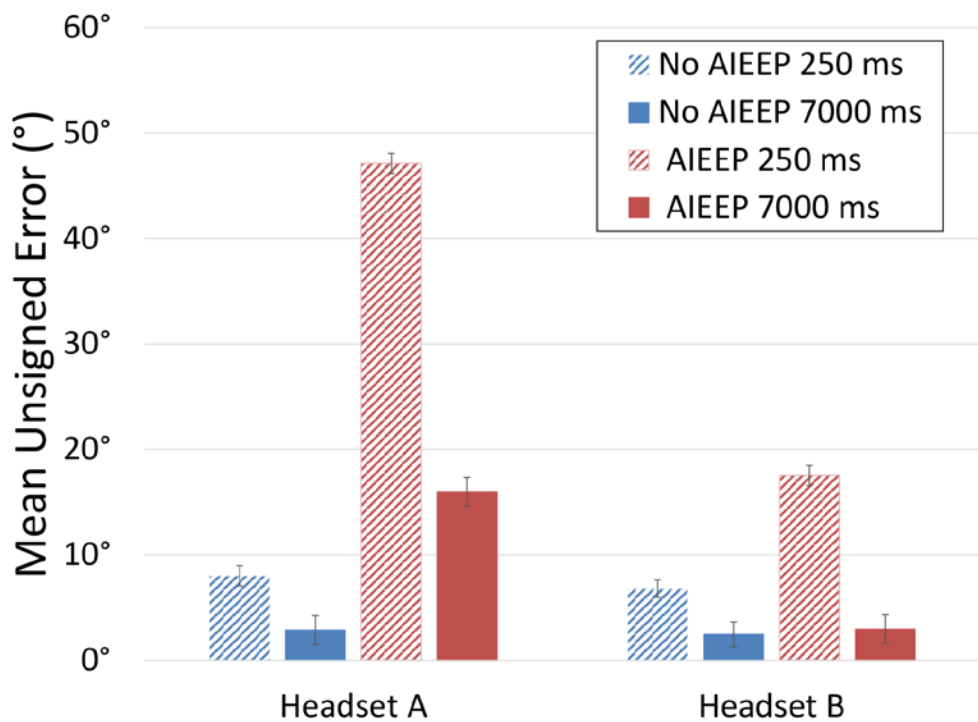

Fig. 4 Comparison of mean unsigned error as a function of prototype used during testing

To test for significance, a 3-factor analysis of covariance (ANCOVA) with subjects as a covariate, was computed for the unsigned error values using prototype, AIEEP use, and signal duration as factors. As expected, the main effect of AIEEP was significant, $F(1,5175) = 438.9$, $p < 0.01$. There was also a main effect of signal duration, $F(1,5175) = 332.1$, $p < 0.01$. However, it is also clear that performance was significantly different as a function of the prototype used, $F(1,5175) = 211.7$, $p < 0.01$. There is an underlying significant interaction of AIEEP and Prototype, $F(1,5175) = 183.0$, $p < 0.01$, as well as the 3-way interaction of Prototype × AIEEP × stimulus duration, $F(1, 5175) = 27.2$, $p < 0.01$. A pairwise comparison of the prototype groups for No-AIEEP trials shows that they were not statistically different, $p = 0.96$, suggesting that the groups differed only in performance with the prototype, and not otherwise.

For this reason, we discuss here the statistical analyses for the subset of participants who used Prototype B. For completeness, the same analyses and graphs are reported for the whole set in Appendices B–K.

3.3 Independent Variables

The design of the experiment was a 4-factor, within-subjects design. The 4 independent variables included in our analyses were AIEEP use, stimulus duration, stimulus level, and sound source azimuth. The primary independent variable was AIEEP usage. However, stimulus duration and source azimuth both have large known effects on auditory localization and were included in all analyses to account for their effects on variability.

Trials also varied by stimulus level and trial type. Stimulus level was randomly set at 1 of 3 levels (65, 70, or 75 dB). Although all of the 250-ms trials were the same, half of the 7000-ms trials were pulsed and the other half were steady. Stimulus level should not alter performance unless it is too low for the signal to be heard. The previous Gamma-IEEP was measured with steady 7000-ms stimuli, but the standard was changed to specify the use of pulsed stimuli. Both types were included to ensure that differences between the Gamma-IEEP and the AIEEP were not due to the stimuli used. To determine whether or not they were significant contributors to error variance, they were initially included in the analysis of signed error. The results of these analyses are reported in Sections 3.3.1 and 3.3.2. Because they were not significant factors, the data in these groups were combined, and this variable was not used as a factor in the remaining analyses.

3.3.1 Pulsed vs. Steady 7000-ms Trials

For the 7000-ms stimuli, there were 2 types of stimuli, pulsed and steady. To determine whether performance on the 7000-ms trials varied as a function of trial type, a 4-factor ANCOVA with subjects as a covariate was computed for the data from the 7000-ms trials[*] with AIEEP use, source angle and level, and trials type as factors. The average signed error, measured for these were 0.35° (pulsed) and 0.31° (steady), and the main effect of stimulus level was not significant, $F(1,458) = 0.003$, $p = 0.97$. Having confirmed that this factor did not statistically alter performance, all of the 7000-ms trials, pulsed and steady, were collapsed into one group.

3.3.2 Stimulus Level

Stimulus level was randomly set at 1 of 3 levels (65, 70, or 75 dB). The mean signed errors observed for these levels were –3.1°, –3.8° and –4.7°, respectively. A 4-factor ANCOVA was computed for the signed error data[†] with AIEEP use, duration, source angle, and level as factors. There was no significant level-related main effect, $F(2, 2592) = 1.00$, $p = 0.366$, and there were no interactions ($p > 0.05$). Therefore, stimulus level was not included as a factor in the subsequent analyses reported here.

3.4 Signed Errors

Signed error gives an estimate of bias if it exists in the data. Potential bias due to front–back reversals are marked by positive errors in the front or negative errors in the back. Listeners will sometimes show a shift toward the interaural or the mid-sagittal axes. These are characteristics of normal human auditory localization. Sometimes, however, the acoustics of the research space are asymmetric, or a loudspeaker is not well equalized, resulting in asymmetric error patterns. Individuals can also show particular biases, resulting from cognitive or auditory factors (for a detailed discussion see Letowski and Letowski 2012; Scharine and Weatherless 2014). Thus, reporting signed error allows us to assess whether errors are due to normal human tendencies or due to problems with the experiment setup. Note that for the relatively small number of participants, perfect symmetry is unlikely.

A 3-factor ANCOVA was computed for signed localization error from the 3 participants using Prototype B. Table 2 summarizes the statistical significance of each of the factors.

[*] Obtained from the participants tested with Prototype B only.
[†] Ibid.

Table 2 Summary of ANCOVA for signed localization error with subjects as a covariate

Source	*df*	*MS*	*F*	*p*	*partial* η^2
Subject[a]	1	19,195.3	48.6	0.001	0.019
AIEEP[a]	1	13,098.0	33.2	0.001	0.013
Stimulus duration[a]	1	41,500.6	105.2	0.001	0.041
Sound source azimuth[a]	35	1607.0	4.1	0.001	0.055
AIEEP × stimulus duration[a]	1	14,560.3	36.9	0.001	0.015
AIEEP × sound source azimuth[a]	35	1376.0	3.5	0.001	0.048
Stimulus duration × sound source azimuth[a]	35	1661.5	4.2	0.001	0.057
AIEEP × stimulus duration × sound source azimuth[a]	35	1323.8	3.4	0.001	0.046
Error	2447	394.6	. . .	. . .	. . .

[a]Significant at $\alpha < 0.05$ level.

The average signed localization error was –5.4°, suggesting a slight bias to respond to the front of the array for stimuli originating from the rear hemisphere and a smaller bias to respond toward the back for stimuli originating near 0°. This negative bias, $F(35, 2447) = 4.07$, $p < 0.001$, is driven by a 3-way interaction of AIEEP use with stimulus duration and sound source, $F(35, 2447) = 3.4$, $p < 0.001$. This negative bias is primarily observed for the 250-ms duration trials while wearing the AIEEP, at –13.1° (Figs. 5 and 6). Note that we expected minimal errors for the 7000-ms trials because the participants can rotate while the sound is playing and therefore resolve any binaural ambiguity from movement-induced cues.

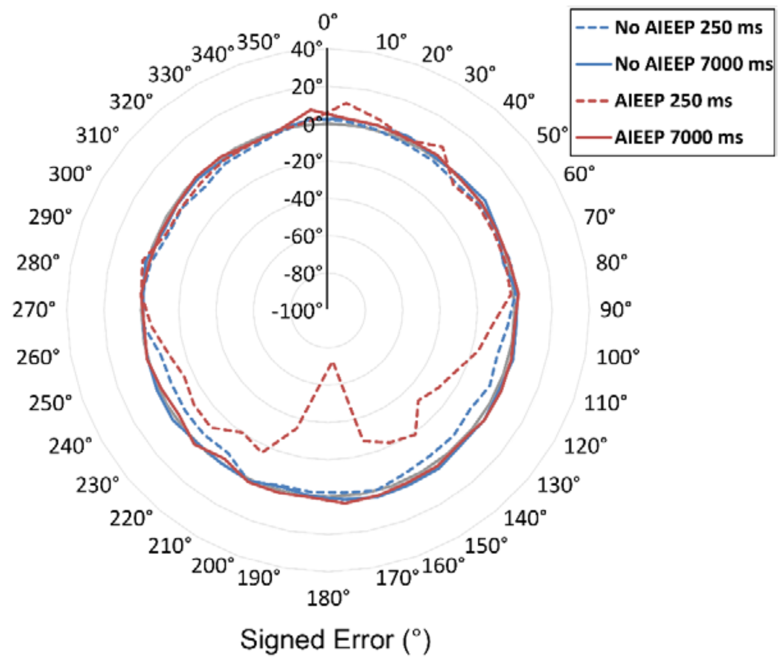

Fig. 5 **Mean signed localization error shown as a function of AIEEP use, sound source azimuth, and stimulus duration (gray circle represents 0° error)**

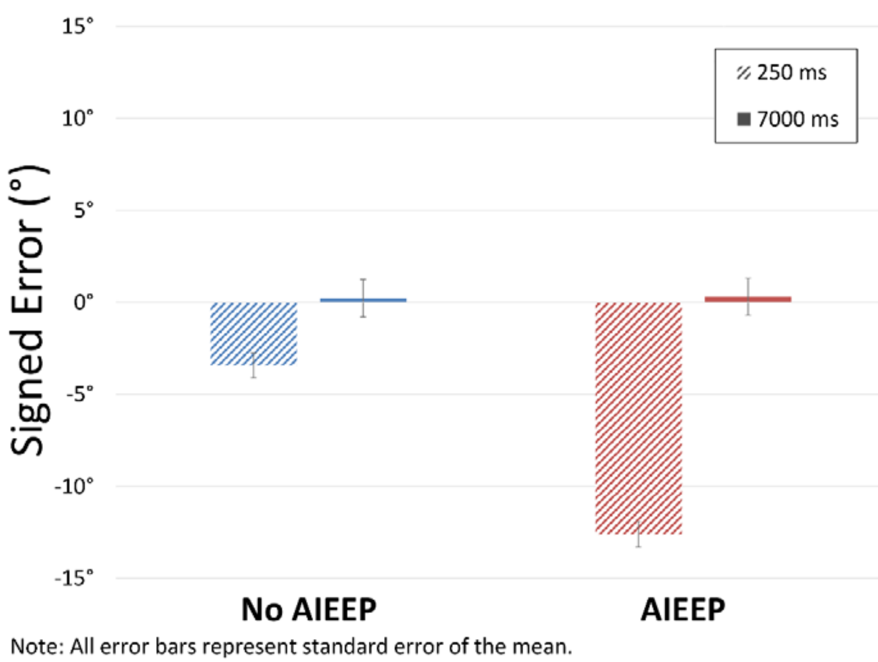

Fig. 6 **Signed localization error as a function of stimulus duration and AIEEP use**

Therefore, there is a front–back asymmetry that reflects a bias to respond more to the front of the array than the rear. This occurs predominantly for the short, 250-ms trials, which end prior to the participant's response and is largest for the AIEEP trials. During the longer trials, the stimulus remains active until the participant

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responds; usually making it possible for the participant to turn until the level of the stimulus is balanced between the 2 ears. Consequently, for these trials, the errors are very small. The tendency to make negative errors has been observed previously in data collected in this loudspeaker array and is thought to be a combination of uncertainty and conservation of effort (Scharine and Weatherless 2014). Participants must rotate the chair farthest for sounds originating from the rear hemisphere. Rotating the chair hundreds of times is tedious, and given uncertainty, participants seem to be more likely to stop short of their perceived target than to over-rotate past it. Fitts' law of human movement posits that accuracy is a function of speed and distance (Fitts 1954). This would predict greater error at locations far from the 0° position especially if participants are motivated to respond quickly. Given that they must make hundreds of responses, it can be assumed that they are motivated to respond quickly and minimize effort. However, this effect is very small for the No-AIEEP trials, suggesting that if the spatial percept is less ambiguous, this tendency is reduced. More importantly, there is no evidence for a systematic right–left bias, especially for the No-AIEEP trials, meaning that differences are due to the device rather than the acoustic conditions.

3.5 Unsigned Errors

Unsigned error is an estimate of the magnitude of an error. If the errors for individual estimates are large, it is not practically important that the average of those errors be near zero. Good auditory localization performance is that in which average unsigned errors are small. In this section we report auditory localization performance measured in terms of unsigned error. However, prior to reporting the data, it is necessary to discuss differences observed for the 2 prototypes.

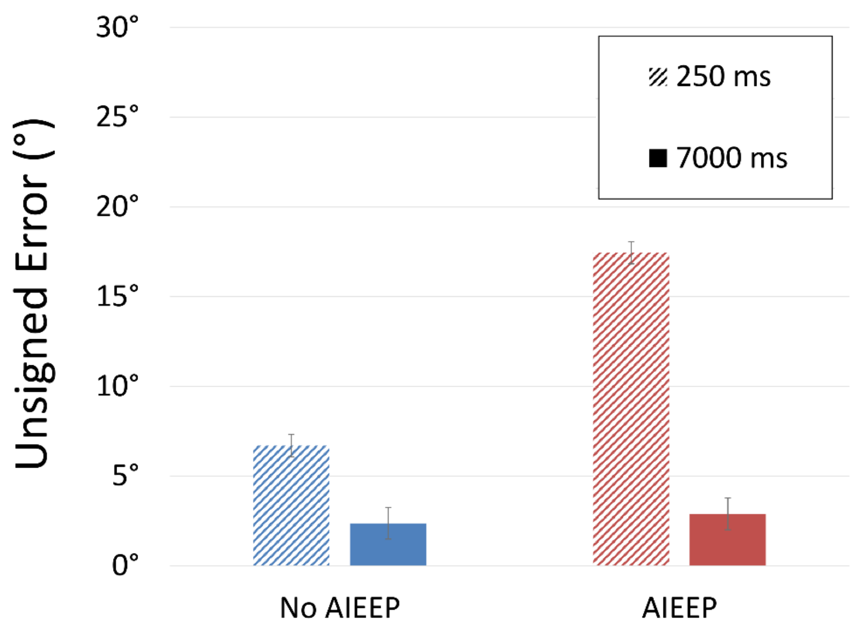
A 3-way ANCOVA with subjects as the covariate was computed for mean unsigned error with AIEEP use, stimulus duration, and sound source azimuth as factors (Table 3).

Table 3 Summary of ANCOVA for unsigned localization error with subjects as a covariate

Source	*df*	*MS*	*F*	*p*	partial η^2
Subject[a]	1	14231.1	43.0	0.001	0.017
AIEEP[a]	1	18198.9	55.0	0.001	0.022
Stimulus duration[a]	1	51107.9	154.4	0.001	0.059
Sound source azimuth[a]	35	1683.9	5.1	0.001	0.068
AIEEP × stimulus duration[a]	1	14995.4	45.2	0.001	0.018
AIEEP × sound source azimuth[a]	35	1306.4	4.0	0.001	0.053
Stimulus duration × sound source azimuth[a]	35	1800.4	5.4	0.001	0.072
AIEEP × stimulus duration × sound source azimuth[a]	35	1372.0	4.1	0.001	0.056
Error	2447	331.0	. . .	. . .	. . .

[a] Significant at $\alpha < 0.05$ level.

Figure 7 shows the main effects of AIEEP usage, $F(1,2447) = 55.0$, $p < 0.01$, stimulus duration, $F(1, 2447) = 154.4$, $p < 0.01$, and their 2-way interaction, $F(1, 2447) = 45.2$, $p < 0.01$. Use of the AIEEP increased average unsigned error by 11° for the 250-ms stimuli, but only increased it by 0.5° for the 7000-ms stimuli. A pairwise comparison showed the difference to be significant for the 250-ms stimuli, $p < 0.01$, but not the 7000-ms stimuli, $p = 0.67$.



Note: All error bars represent standard error of the mean.

Fig. 7 Mean unsigned error shown as a function of AIEEP usage and stimulus duration

There was a main effect of sound source azimuth, $F(35, 2447) = 5.1$, $p < 0.01$, and a significant interaction of stimulus duration and sound source azimuth, $F(35, 2447) = 5.4$, $p < 0.01$. Overall, errors for the 7000-ms stimuli are very small at most horizontal azimuths. In contrast, there are large errors in the rear hemisphere for the 250-ms stimuli that are probably due to back–front reversals. This is discussed in the following section.

Figures 8 and 9 show the 3-way interaction of AIEEP use with stimulus duration and sound source azimuth, $F(35, 2447) = 4.1$, $p < 0.01$, that appears to be the result of larger errors near 180° for the 250-ms stimuli and the increase in these errors due to AIEEP use.

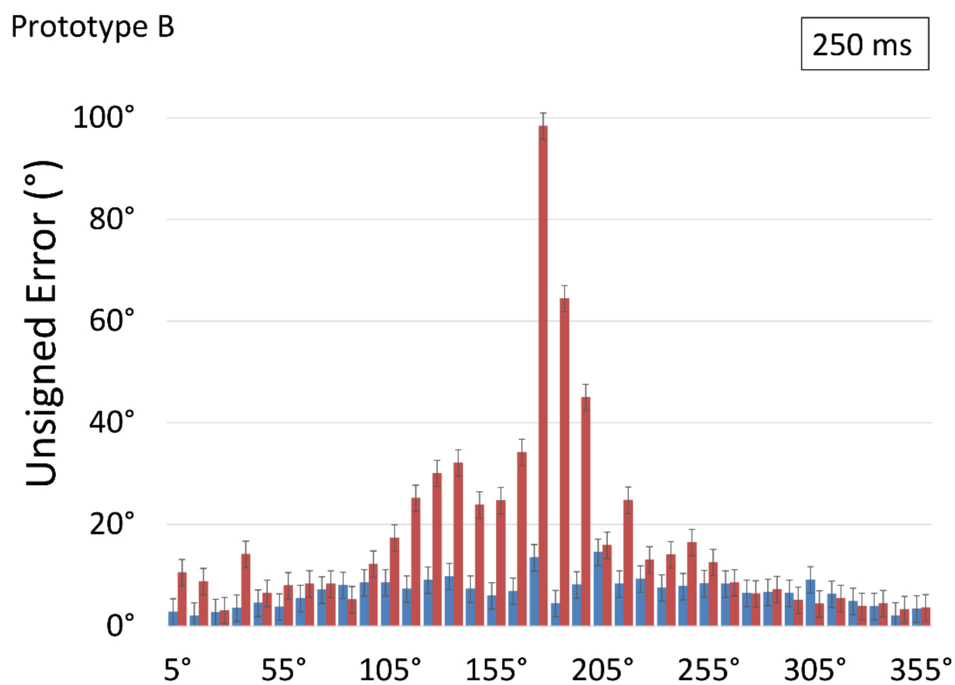


Fig. 8 Mean unsigned error shown as a function of AIEEP use and sound source azimuth for the 250-ms trials

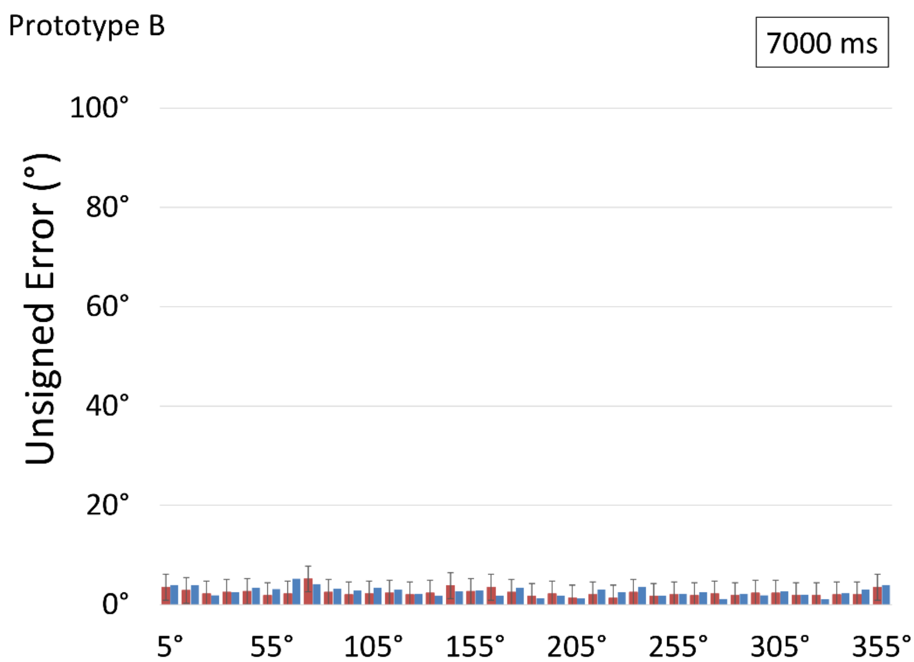


Fig. 9 Mean unsigned error shown as a function of AIEEP use and sound source azimuth for the 7000-ms trials

3.6 Reversals

Because front–back confusions are often large errors, especially for sources near 0° and 180°, they are the primary spatial auditory concern for users of TCAPS devices. Localization blur usually results in a slight increase in the average magnitude of errors. However, visual feedback will allow the listener to refine the auditory estimate if the target is within the listener's field of view. Conversely, front-back confusions, also known as reversals, can cause very large errors (Scharine 2009). Therefore, the data were coded for responses that were most likely due to reversals so that we could determine the degree to which reversals are the source of localization error.

For each trial, the error was compared with what the error would have been if the sound source had been in the reverse hemisphere. If $T < 180°$, the reversal T_r was computed as follows:

$$T_r = 180° - T, \tag{1}$$

else:

$$T_r = 540° - T. \tag{2}$$

The error for this reversed azimuth angle was computed by subtracting it from the estimated angle:

$$D_r = E - T_{r.} \tag{3}$$

Reversals for sounds originating from near 0° or 180° are large. Conversely, if a sound originated from near 90° or 270°, it is difficult to determine whether an error is due to a front–back error or to localization blur. In practice, the effect is the same. Therefore, we include the limit that the original error must be greater than 30° for the trial to be coded as a reversal A trial was coded as a reversal if the unsigned error was greater than 30° and if the source estimate was within 15° of T_r; that is, $E_r \leq 15°$. Thus if

$$D_r \leq 15° \;\&\; |D| \geq 30° \stackrel{\text{def}}{=} \text{reversal.} \tag{4}$$

Overall, only 83 of a total 2592 trials (3.2%) were coded as a reversal. It is clear that reversals account for much of the difference between the AIEEP and No-AIEEP conditions (Fig. 10). Most of the reversals observed were for the short-duration stimuli during the AIEEP condition at angles near 180° (Fig. 11).

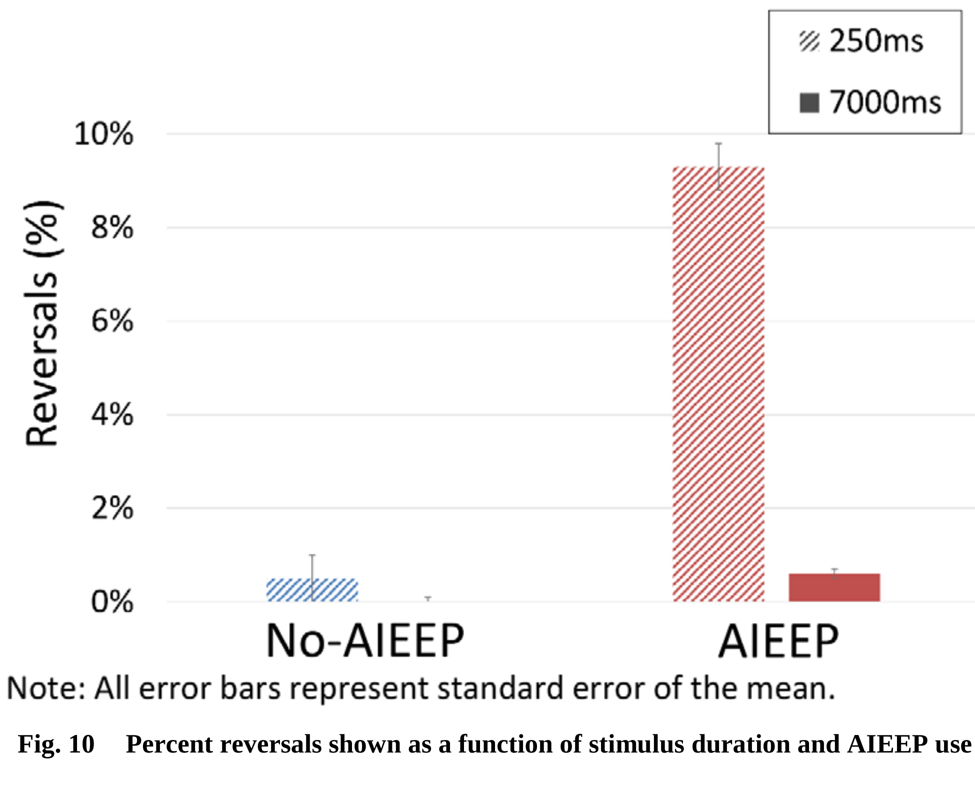


Fig. 10 Percent reversals shown as a function of stimulus duration and AIEEP use

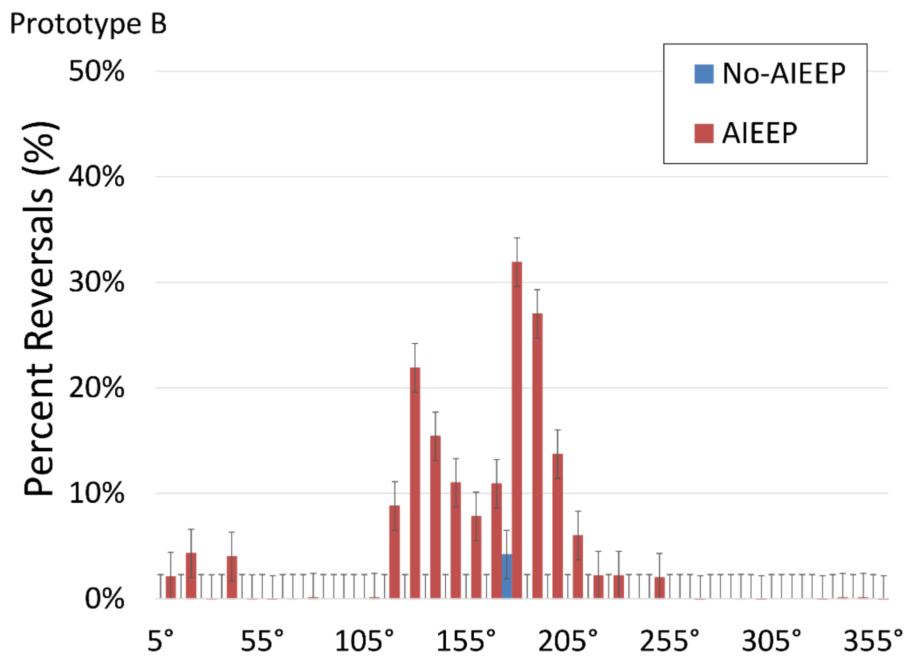


Fig. 11 **Percent reversals shown as a function of sound source azimuth and AIEEP use**

3.7 Distribution of Responses

When examining the results of auditory localization measures for TCAPS devices, it is helpful to understand where errors are probable and what their sources are. If responses are coded by whether they were "correct", meaning within 5° of the source loudspeaker; "blur", meaning within 15° of the source loudspeaker; or "reversed", meaning within 15° of the reversed loudspeaker, we can draw some conclusions about how the TCAPS affects auditory spatial acuity. Figure 12 shows these data for the 250-ms stimuli. The errors due to blur are fairly similar for both the No-AIEEP (39%) and the AIEEP (34%) conditions. However, the overall proportion of loudspeakers identified correctly within 15° is significantly greater for the No-AIEEP condition (85%) than the AIEEP condition (66%). Further, the proportion of errors is within 15° of a reversal, with increases from 1% to 7%.

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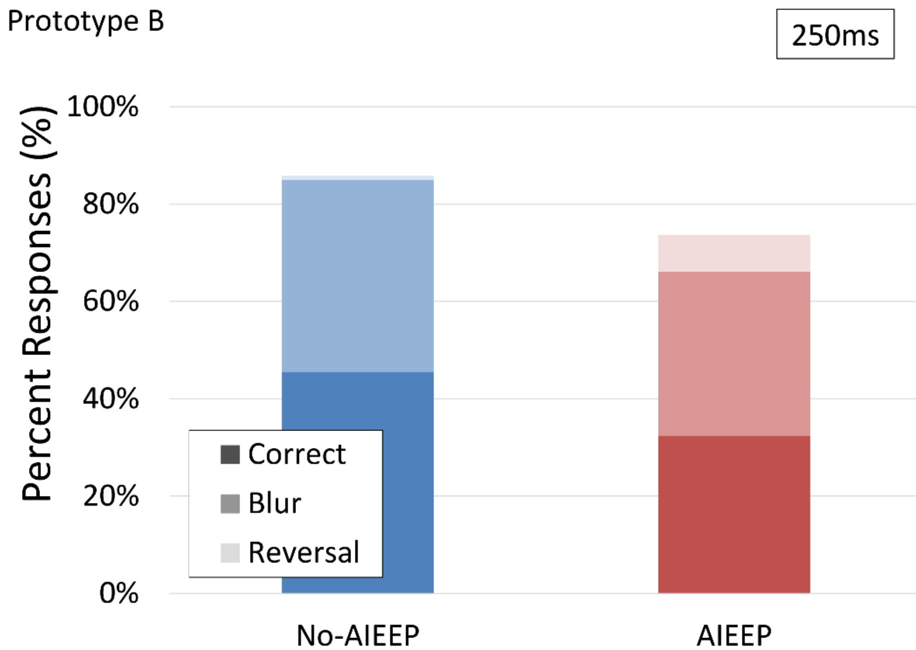

Fig. 12 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal; shown as a function of AIEEP use

Figures 13 and 14 show the distribution of responses to 250-ms stimuli as a function of source angle for the No-AIEEP condition and the AIEEP condition. There is reduced spatial sensitivity for the rear hemisphere where there are clearly visible increases in blur and reversals, especially for the AIEEP condition. This is presumed to be due to the alteration of monaural cues caused by the insertion of the earphone tips.

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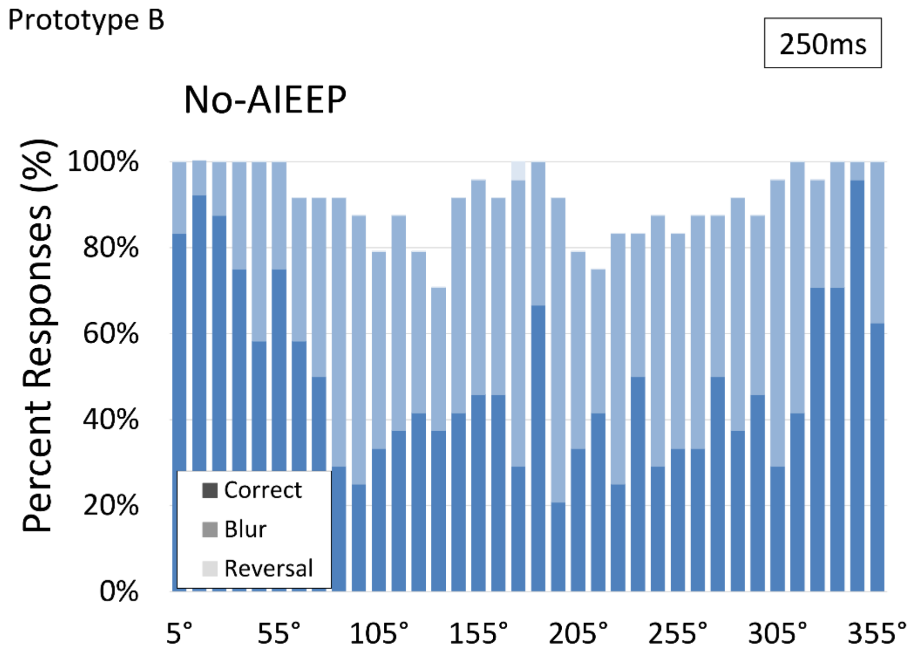


Fig. 13 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal; shown for the No-AIEEP condition; shown as a function of source angle (°)

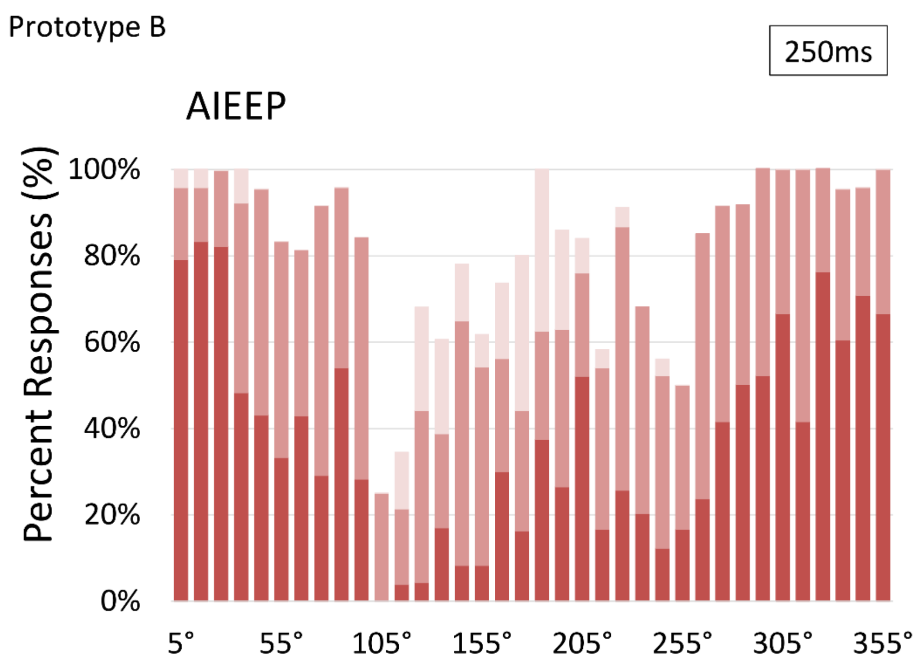
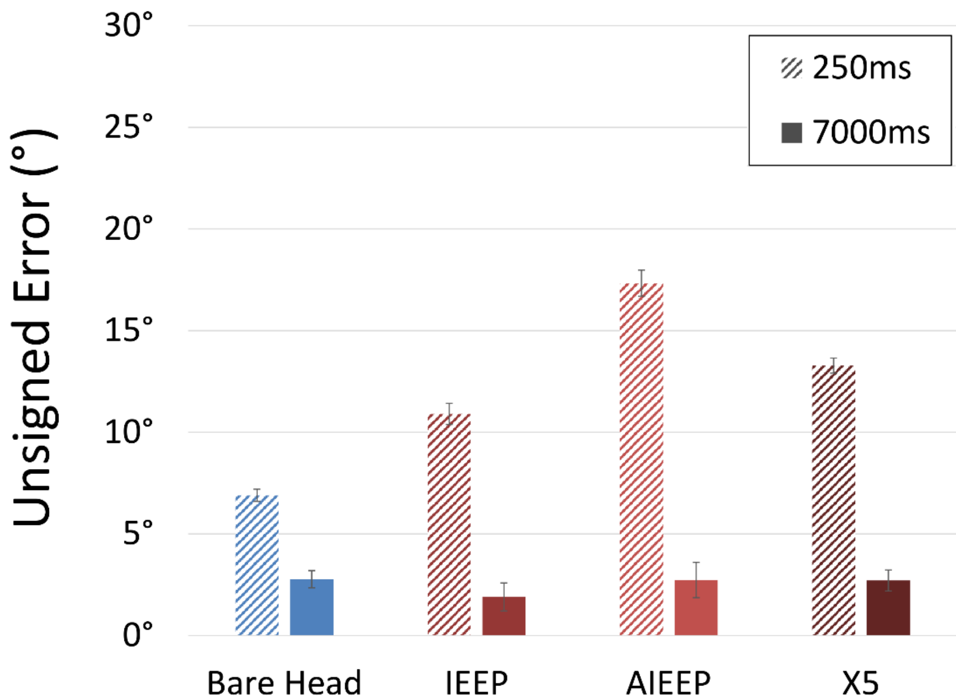


Fig. 14 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal; shown for the AIEEP condition; shown as a function of source angle (°)

To give a sense of how the AIEEP compares with the previous prototype (IEEP) and with another TCAPS device (Invisio-X5), data from 2 recent studies (Scharine et al. 2016; Domanico et al. 2017) were combined with the current data. The test methods were the same, with the exception that all of the 7000-ms stimuli were of the steady type. Five participants were tested using the IEEP, and 12 participants were tested with the X5. The data for the bare-head condition were combined across subjects. Figure 15 shows the average unsigned error, graphed as a function of stimulus duration and device worn. Table 4 summarizes the results of an ANCOVA computed for the unsigned error data. There was a main effect for Device, as well as all interactions with Device, $p < 0.05$. A pairwise comparison for the 250-ms stimuli confirmed that all devices were significantly different from each other and from the bare-head condition, $p < 0.001$. Conversely, for the 7000-ms stimuli, the only device that differed significantly from the bare-head condition was the AIEEP $p = 0.022$.



Note: All error bars represent standard error of the mean.

Fig. 15 Unsigned error shown as a function of stimulus duration and device worn

Table 4 Summary of the ANCOVA computed for unsigned variance for the combined data from the AIEEP, IEEP, and X5-Invisio

Source	*df*	*MS*	*F*	*p*	*partial* η^2
Subject	1	11,626.8	40.6	0.001	0.003
Device[a]	3	10,912.3	38.1	0.001	0.008
Stimulus duration[a]	1	19,4166.0	677.6	0.001	0.048
Sound source azimuth[a]	35	5775.2	20.2	0.001	0.050
Device × stimulus duration[a]	3	12,707.5	44.3	0.001	0.010
Device × sound source azimuth[a]	105	843.4	2.9	0.001	0.022
Stimulus duration × sound source azimuth[a]	35	5035.4	17.6	0.001	0.044
Device × stimulus duration × sound source azimuth[a]	105	11,56.3	4.0	0.001	0.031
Error	13,451	286.6	. . .	. . .	. . .

[a] Significant at $\alpha < 0.05$ level.

Figures 16 and 17 show the distribution of responses observed for the 3 devices for the 250- and 7000-ms data, respectively. Generally, it seems that the data for the AIEEP are worse in percent correct and had more reversals. However, the percent within 15° of correct (blur) was similar for the AIEEP and the TCAPS. Whereas, even though a higher percent correct was measured for the X5-Invisio, the percentage of trials within 15° of the correct loudspeaker was higher for the IEEP. Recall that the data shown are from 3 groups of participants who may have underlying differences in baseline localization ability. However, the statistical analysis does take these underlying differences into account. The size of these differences is relatively small, and given the production issues encountered with these prototypes, it is unlikely that they are damning of the prototype itself, but they do signal that there are issues that need resolution.

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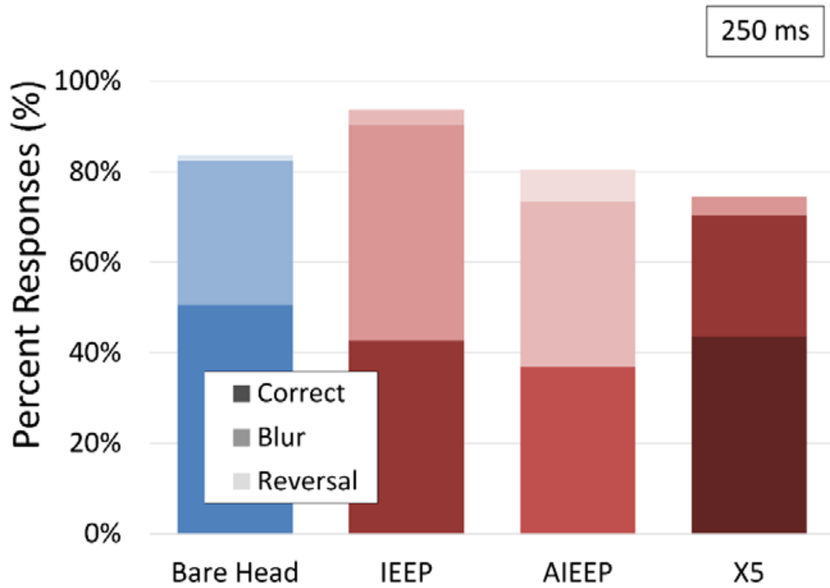

Fig. 16 Response distribution of the data from the 250-ms trials measured for the AIEEP, IEEP, and X5-Invisio devices

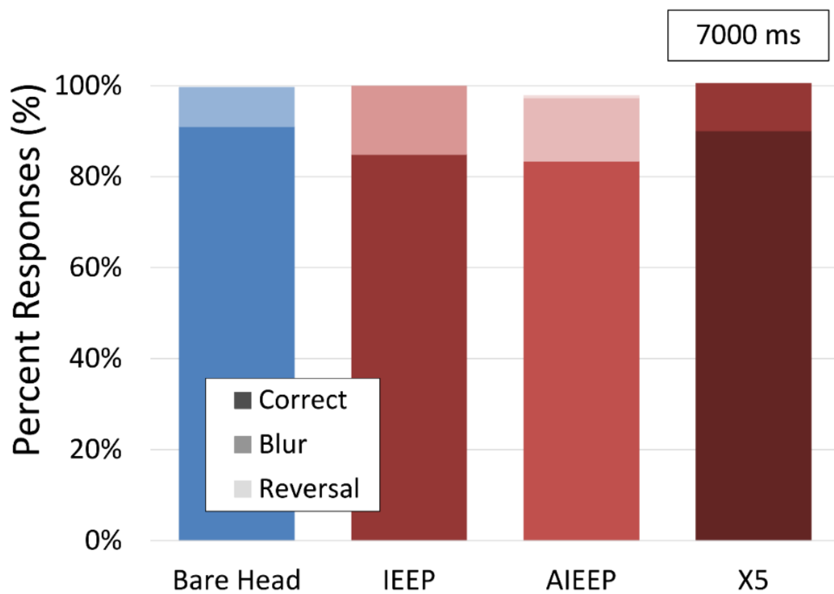

Fig. 17 Response distribution of the data from the 7000-ms trials measured for the AIEEP, IEEP, and X5-Invisio devices

4. Conclusion

Auditory localization accuracy was measured for participants wearing the AIEEP, a prototype TCAPS that also provides eye protection. Testing was conducted using one of the methods recently proposed to the ANSI/ASA as a standard measurement of auditory localization ability. All participant-wise performance was reported in comparison with performance with their ears unoccluded.

There were significant differences observed for the 2 prototypes tested. As a result, the data in the main body of the paper are for one device; Appendices B–K contain the data for both devices and the set as a whole.

Listeners using the Prototype B AIEEP showed reasonably good localization accuracy with the device. The AIEEP, after taking into account the known effects of sound source azimuth and stimulus duration, increase the magnitude of average errors from 4.5° to 10.2°. This was mostly due to errors observed for the short-duration (250-ms) stimuli, where the average unsigned error increased from 7° to 17°.

In contrast, the average unsigned error observed for the 250-ms trials with Prototype A AIEEP was 47.2°, an increase of 39° from the bare-head condition. Similarly, for the 7000-ms trials, the average unsigned error was 16.1°, an increase of 13°. Since there were no physical differences between the 2 prototypes, it must be assumed that the differences were due to issues with the electronic processor of the devices, suggesting that there is a need to ensure consistent production quality.

Note that, generally, auditory localization performance is nearly perfect for the 7000-ms stimuli because participants can rotate while the sound is still playing and essentially turn until the sound is balanced between the 2 ears. This eliminates the ambiguity that results from binaural cues. The 7000-ms stimuli are included in the standard method because they highlight problems with signal processing that may occur due to the electronics of a device. In this case, the unsigned error (16.1°) observed for the 7000-ms trials with the Prototype A AIEEP was actually nearly as high as the unsigned error (17°) observed for the 250-ms trials with Prototype B. This is evidence that something was malfunctioning in Prototype A.

Auditory localization ability is one of several factors to be considered when determining the quality of auditory situation awareness provided by a TCAPS device (Clasing and Casali 2014). Other factors include one's ability to detect, recognize, and identify sounds, including face-to-face and radio communications. Further acoustic testing is needed to ensure that hearing protection requirements are met. However, from the standpoint of auditory localization as tested in the current study, the AIEEP has a minimal impact on localization performance, allowing the user to retain the majority of his or her auditory spatial capabilities.

5. References

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Appendix A. Auditory Localization Metrics

A.1 Signed Error (D)

The difference in degrees D between the localization estimate E and the sound source location T. If $E > 0°$ it means that the estimate was between the sound source location and 180°. If $E < 0°$ it means that the estimate was between 0° and the sound source location.

A.2 Unsigned Error ($|D|$)

$|D|$ = the absolute value, or magnitude of D.

A.3 Reverse Location (T_r)

If T < 180°: $T_r = 180° - T$, otherwise: $T_r = 540° - T$.

A.4 Reversal Error ($|D_r|$)

The difference in degrees $|D_r|$ between the localization estimate E and the reversal of the sound source location T_r.

A.5 Response Types

Correct: $|D| \leq 5°$

Blur: $|D| > 5°$ & $|D| \leq 15°$

Reversal: $|D| > 30°$ & $|D_r| \leq 15°$

Appendix B. Unsigned Data: All

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Source	***df***	***MS***	***F***	***p***	***partial η²***
Subject[a]	1	14214.7	14.1	0.001	0.005
AIEEP[a]	1	28,9350.2	24.1	0.001	0.089
Stimulus duration[a]	1	21,8384.2	370.6	0.001	0.068
Sound source azimuth[a]	35	5285.0	9.0	0.001	0.059
AIEEP × stimulus duration[a]	1	94,745.2	159.7	0.001	0.031
AIEEP × sound source azimuth[a]	35	2987.4	5.1	0.001	0.034
Stimulus duration × sound source azimuth[a]	35	5169.5	8.8	0.001	0.057
AIEEP × stimulus duration × sound source azimuth[a]	35	2957.3	5.0	0.001	0.034
Error	5039	589.3	. . .	. . .	. . .

[a] Significant at α < 0.05 level.

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Appendix C. Response Distribution: All

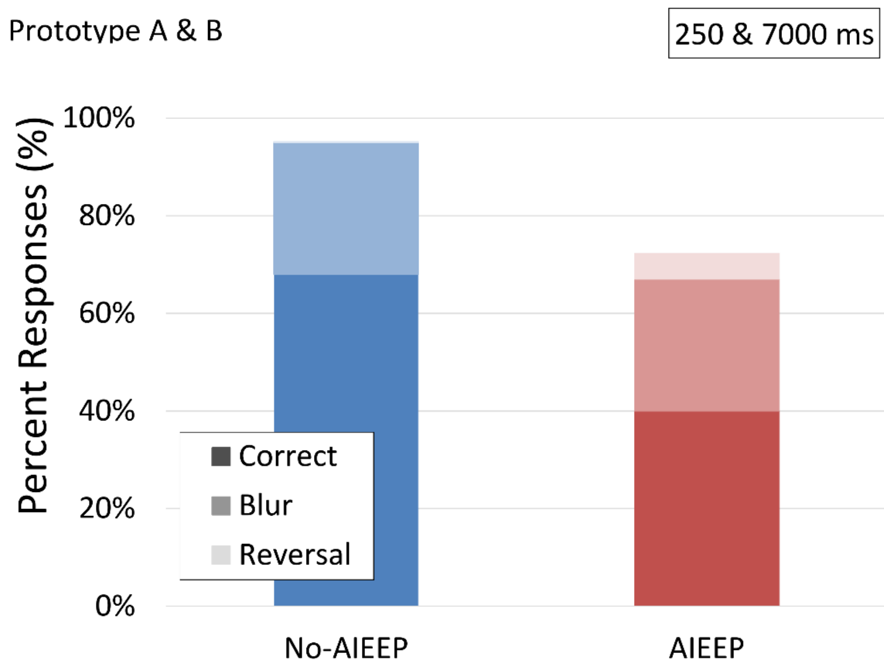

Fig. C-1 Proportion of responses that were correct, were blurred, or a reversal, shown as a function of AIEEP use

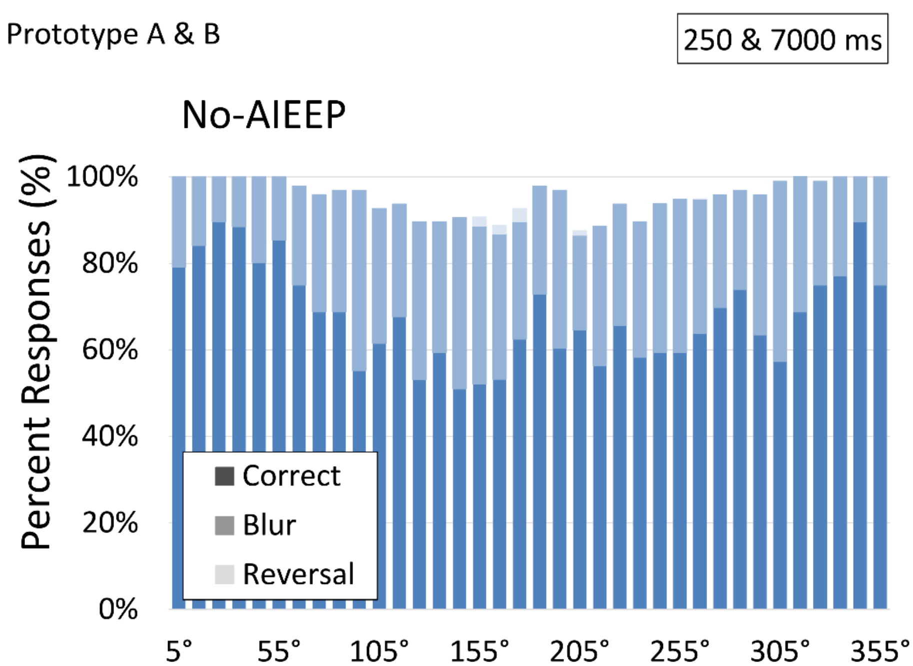

Fig. C-2 Proportion of responses that were correct, were blurred, or a reversal, shown as a function of angle for the No-AIEEP trials

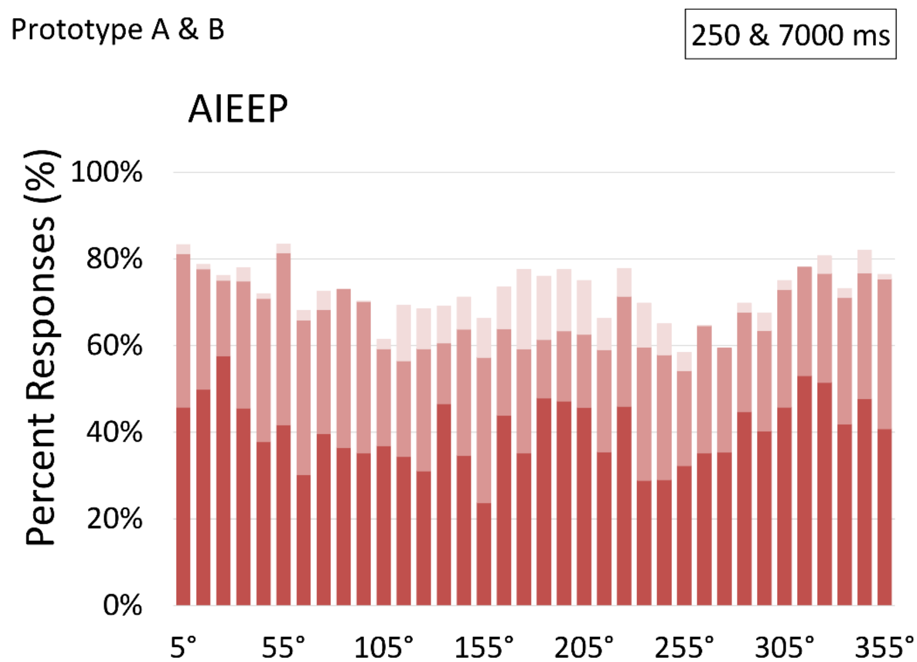

Fig. C-3 Proportion of responses that were correct, were blurred, or a reversal, shown as a function of angle for the AIEEP trials

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Appendix D. Response Distribution: All 250-ms Trials

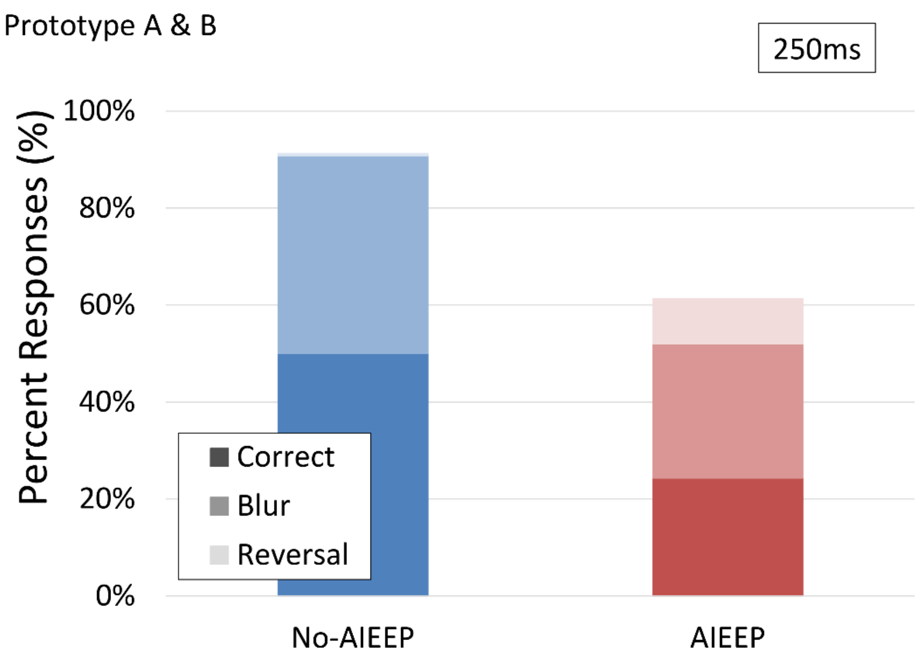

Fig. D-1 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal, shown as a function of AIEEP use

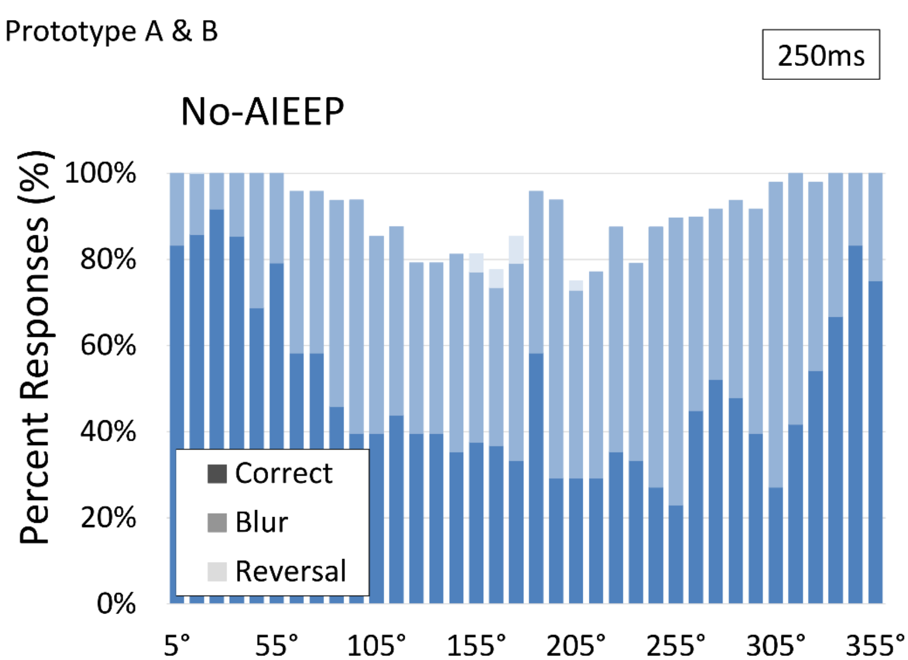

Fig. D-2 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the No-AIEEP trials

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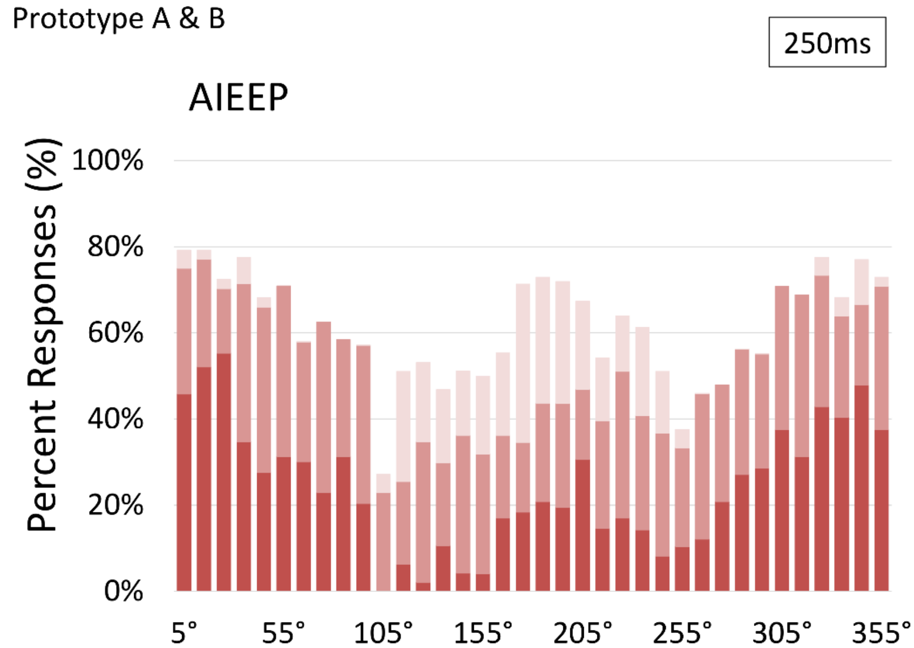

Fig. D-3 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the AIEEP trials

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Appendix E. Response Distribution: All 7000-ms Trials

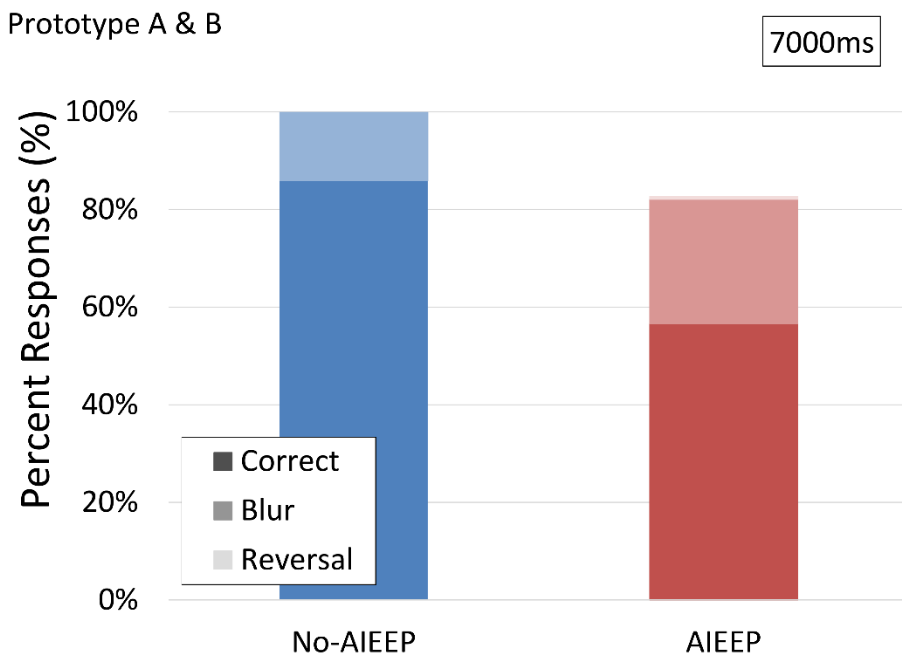

Fig. E-1 Proportion of responses to 7000-ms stimuli that were correct, were blurred, or a reversal, shown as a function of AIEEP use

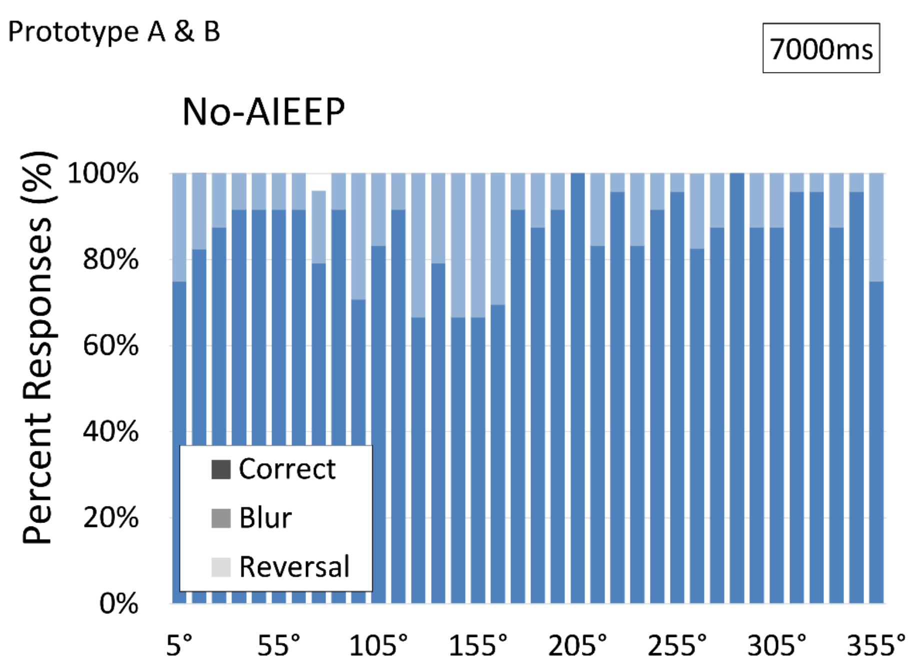

Fig. E-2 Proportion of responses to 7000-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the No-AIEEP trials

Prototype A & B

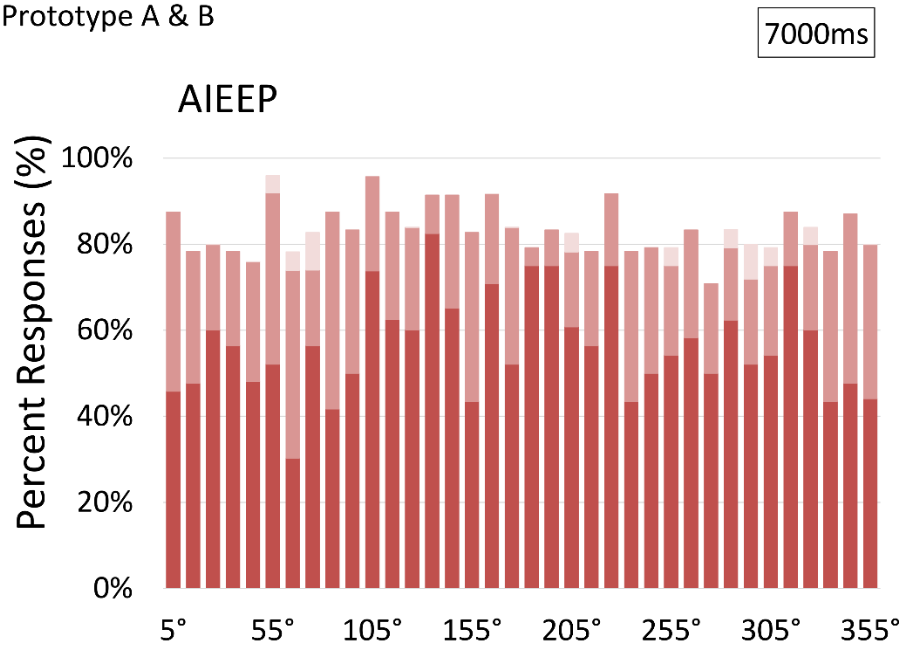

Fig. E-3 Proportion of responses to 7000-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the AIEEP trials

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Appendix F. Response Distribution: Prototype A Only

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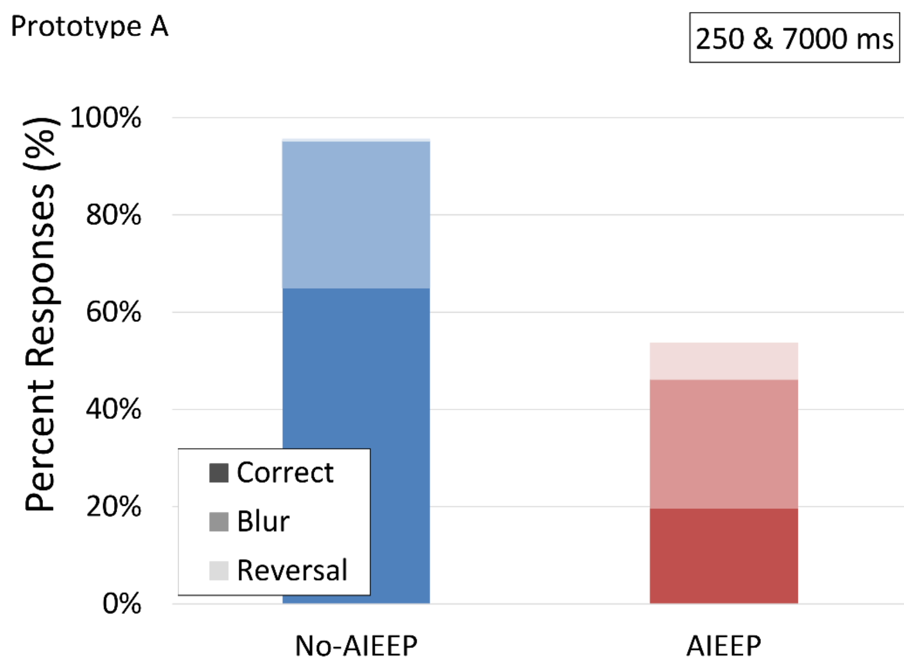

Fig. F-1 Proportion of responses that were correct, were blurred, or a reversal, shown as a function of AIEEP use: Prototype A only

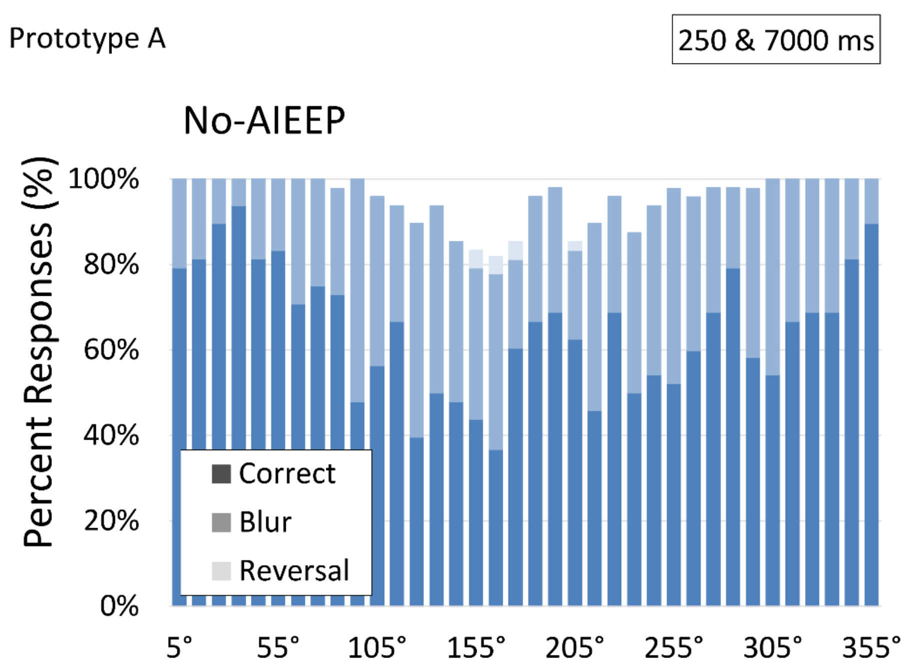

Fig. F-2 Proportion of responses that were correct, were blurred, or a reversal, shown as a function of angle for the No-AIEEP trials: Prototype A only

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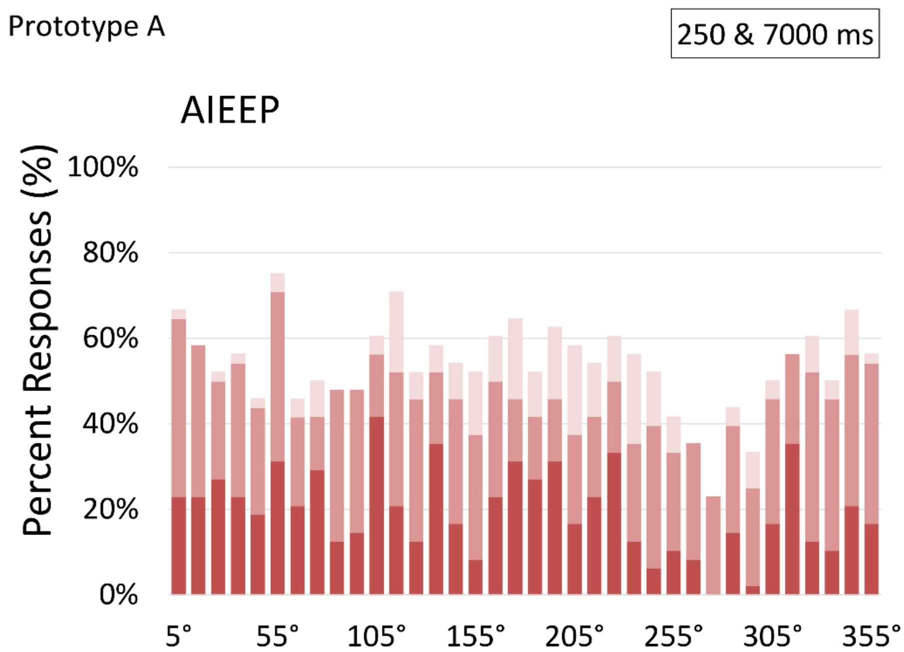

Fig. F-3 Proportion of responses that were correct, were blurred, or a reversal, shown as a function of angle for the AIEEP trials: Prototype A only

Appendix G. Response Distribution: Prototype A 250-ms Trials

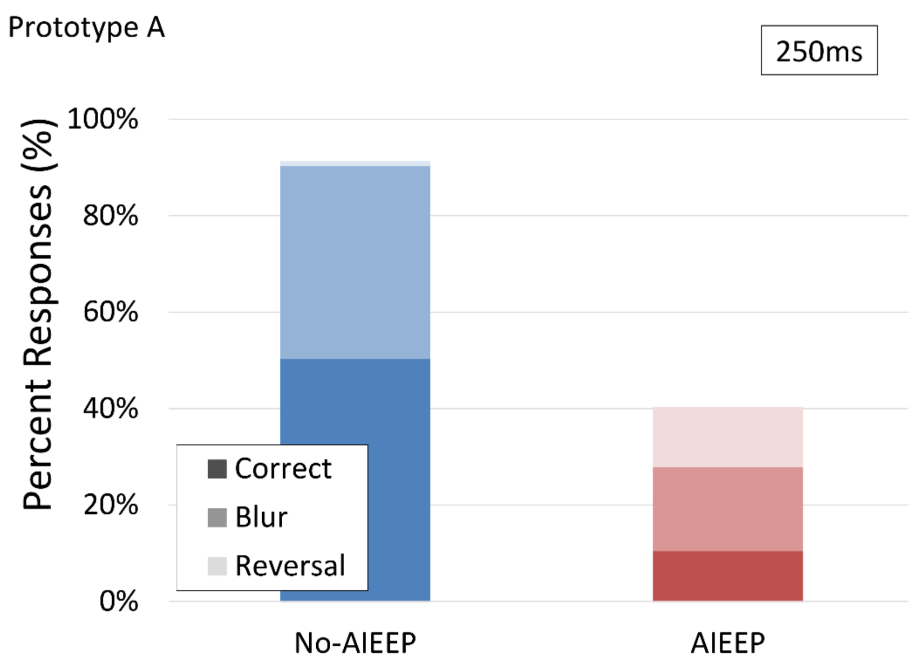

Fig. G-1 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal, as a function of AIEEP use: Prototype A only

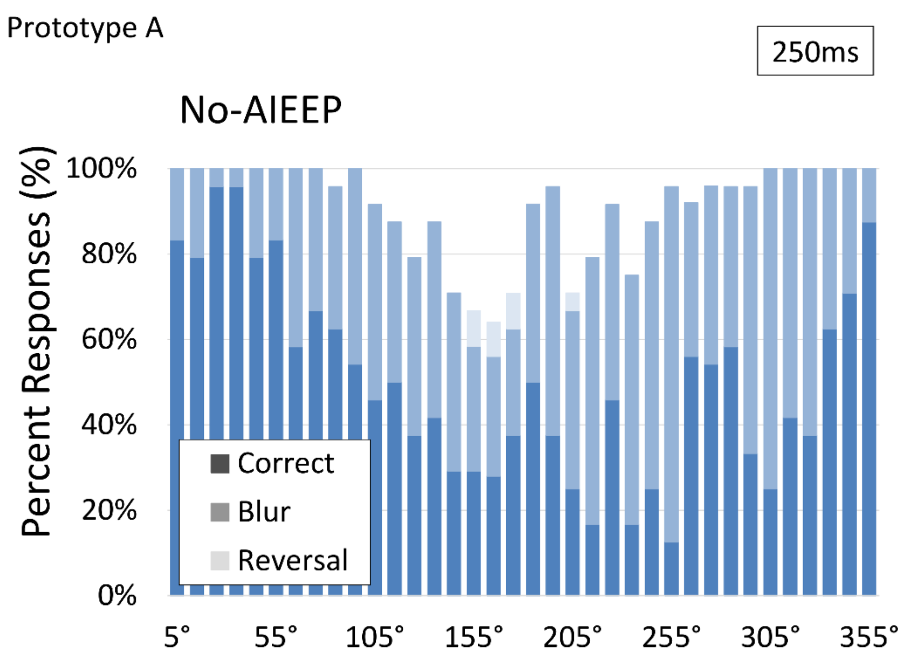

Fig. G-2 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the No-AIEEP trials: Prototype A only

Prototype A

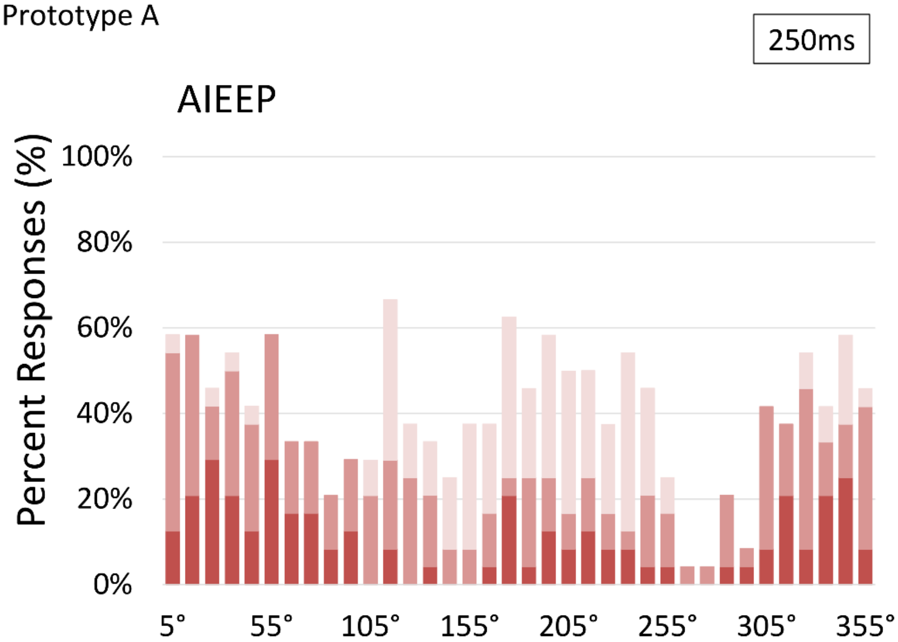

Fig. G-3 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the AIEEP trials: Prototype A only

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Appendix H. Response Distribution: Prototype A 7000-ms Trials

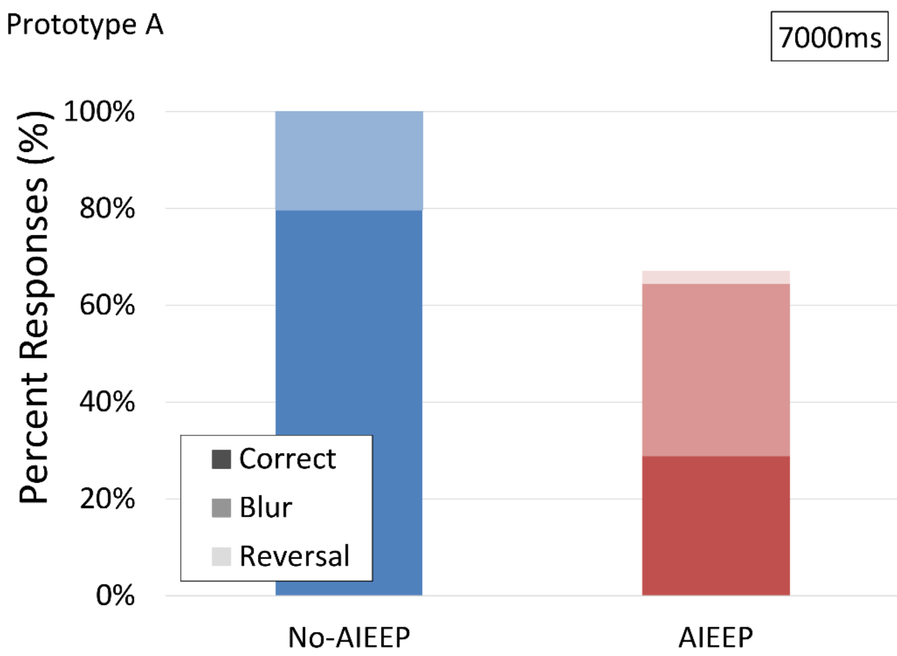

Fig. H-1 Proportion of responses to 7000-ms stimuli that were correct, were blurred, or a reversal, shown as a function of AIEEP use: Prototype A only

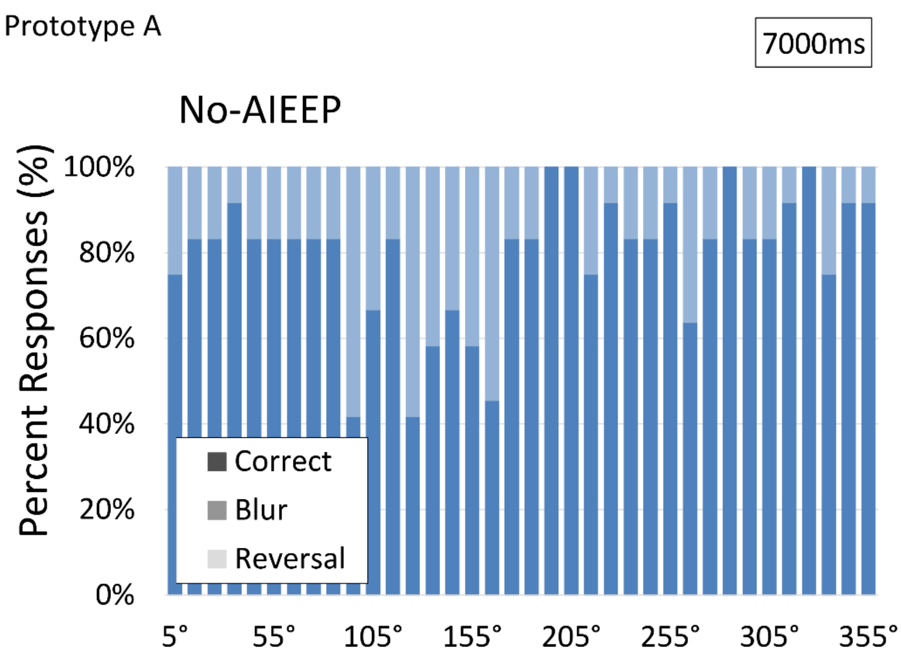

Fig. H-2 Proportion of responses to 7000-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the No-AIEEP trials: Prototype A only

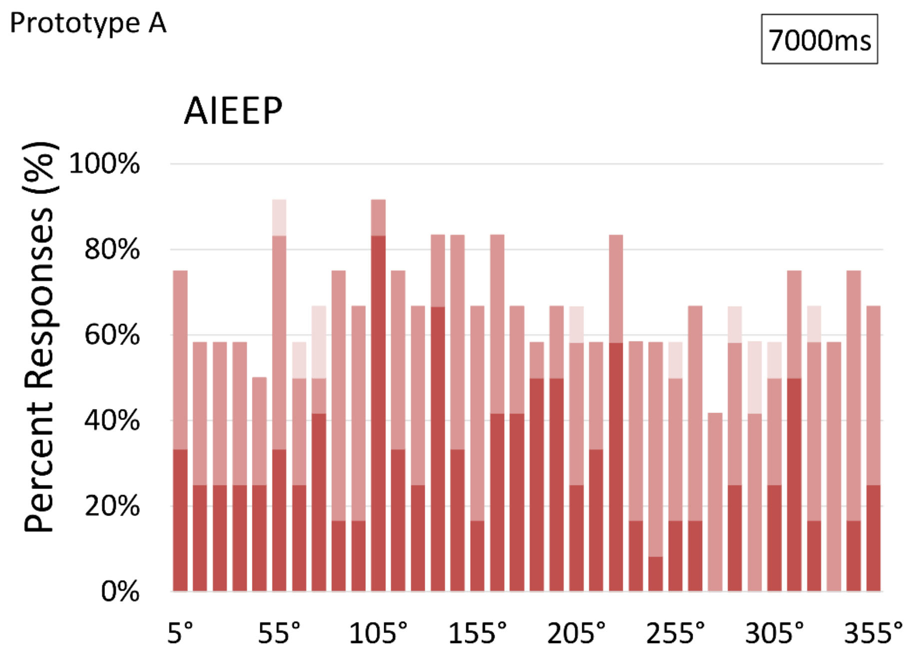

Fig. H-3 Proportion of responses to 7000-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the AIEEP trials: Prototype A only

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Appendix I. Response Distribution: Prototype B Only

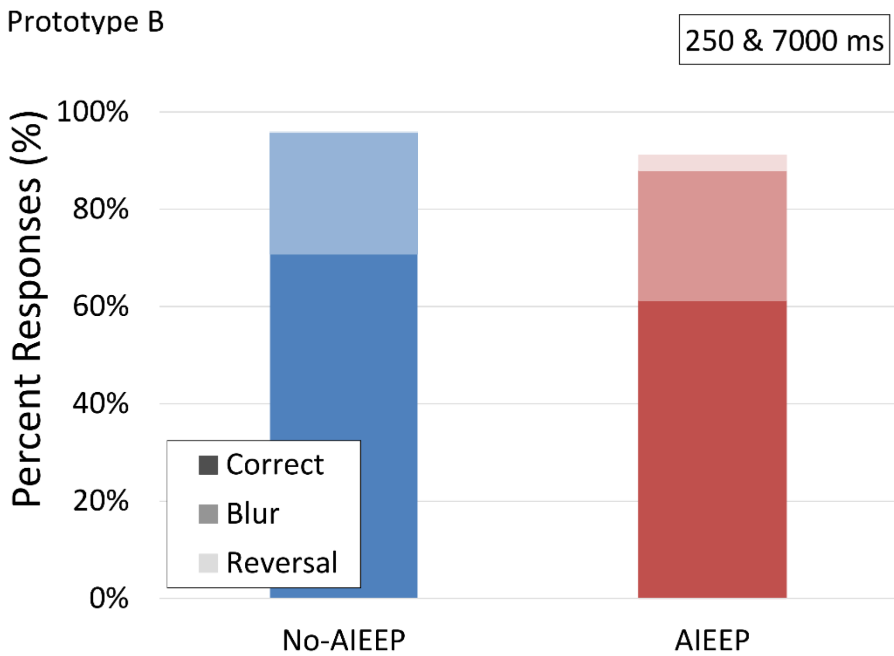

Fig. I-1 Proportion of responses that were correct, were blurred, or a reversal, shown as a function of AIEEP use: Prototype B only

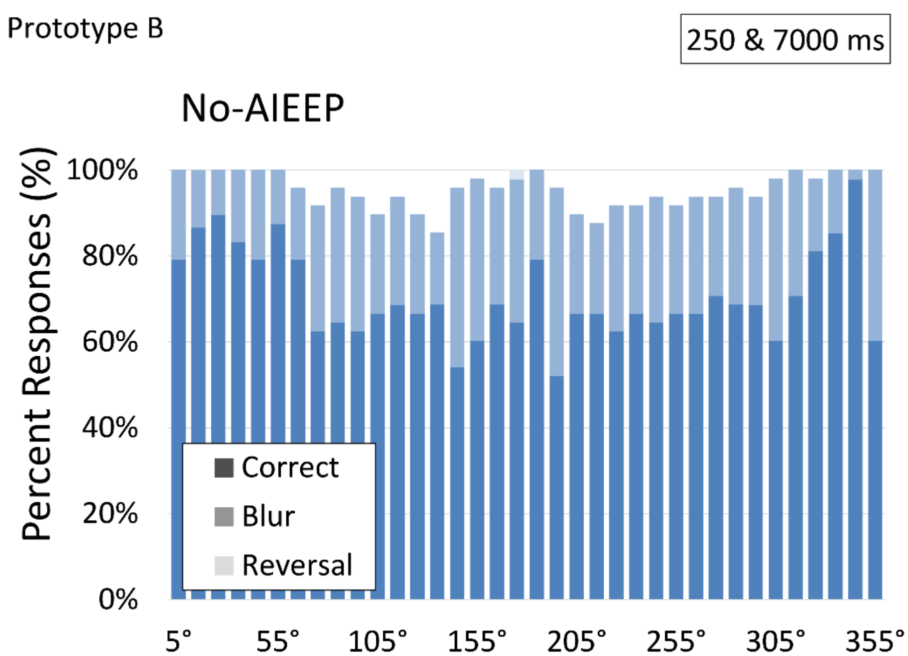

Fig. I-2 Proportion of responses that were correct, were blurred, or a reversal, shown as a function of angle for the No-AIEEP trials: Prototype B only

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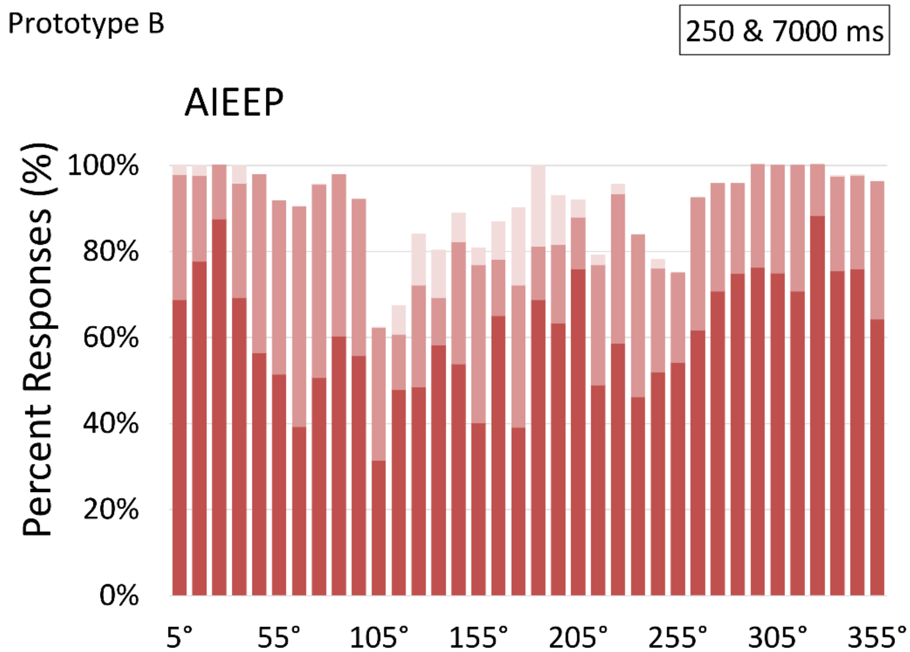

Fig. I-3 Proportion of responses that were correct, were blurred, or a reversal, shown as a function of angle for the AIEEP trials: Prototype B only

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Appendix J. Response Distribution: Prototype B 250-ms Trials

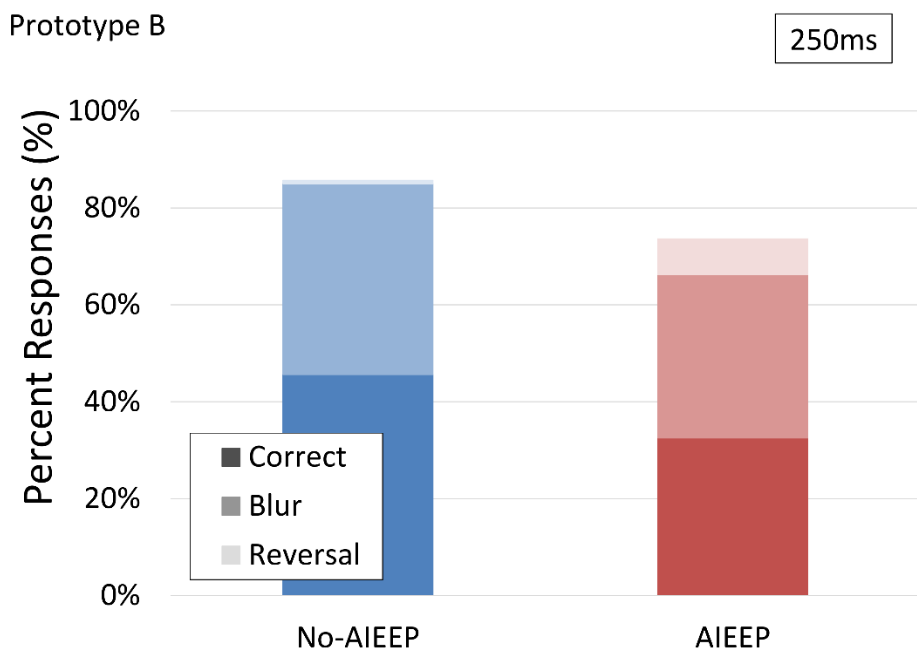

Fig. J-1 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal, as a function of AIEEP use: Prototype B only

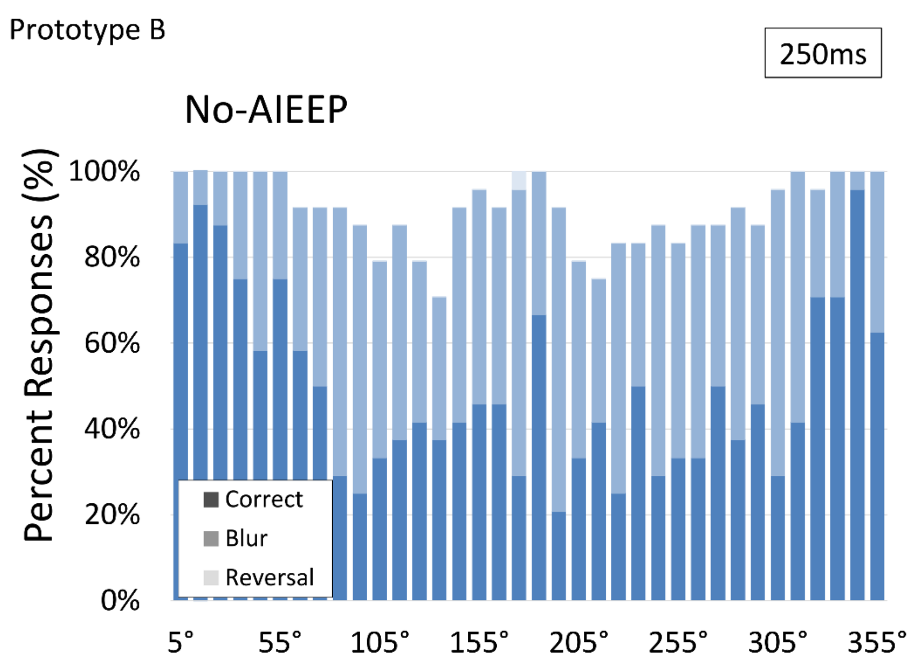

Fig. J-2 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the No-AIEEP trials: Prototype B only

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Prototype B

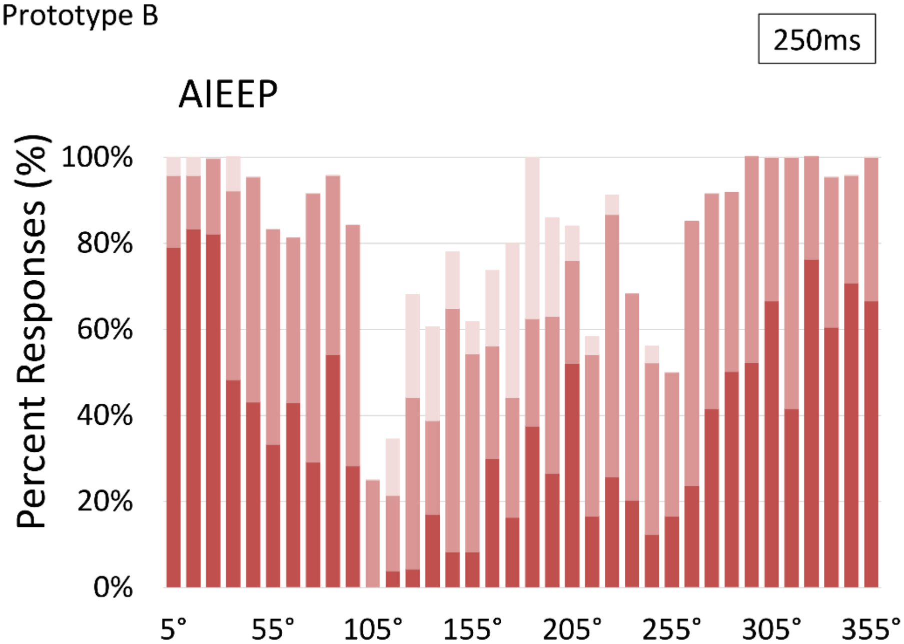

Fig. J-3 Proportion of responses to 250-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the AIEEP trials: Prototype B only

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Appendix K. Response Distribution: Prototype B 7000-ms Trials

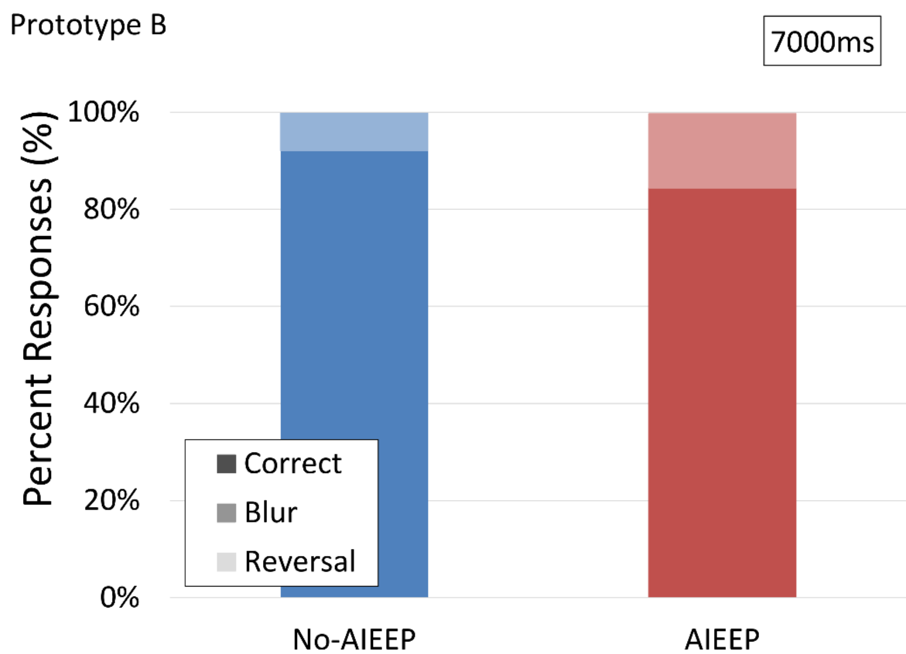

Fig. K-1 Proportion of responses to 7000-ms stimuli that were correct, were blurred, or a reversal, shown as a function of AIEEP use: Prototype B only

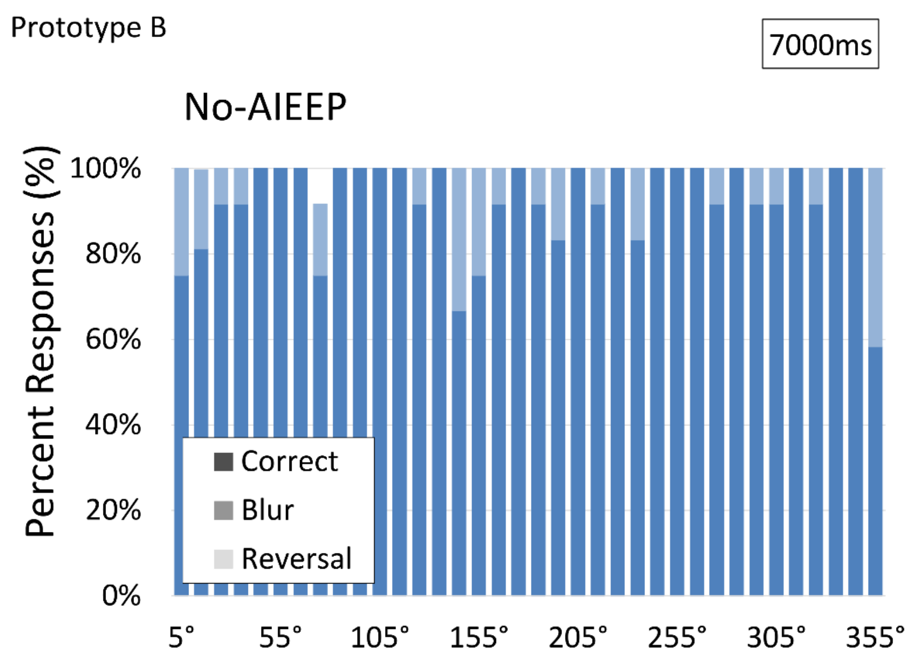

Fig. K-2 Proportion of responses to 7000-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the No-AIEEP trials: Prototype B only

Prototype B

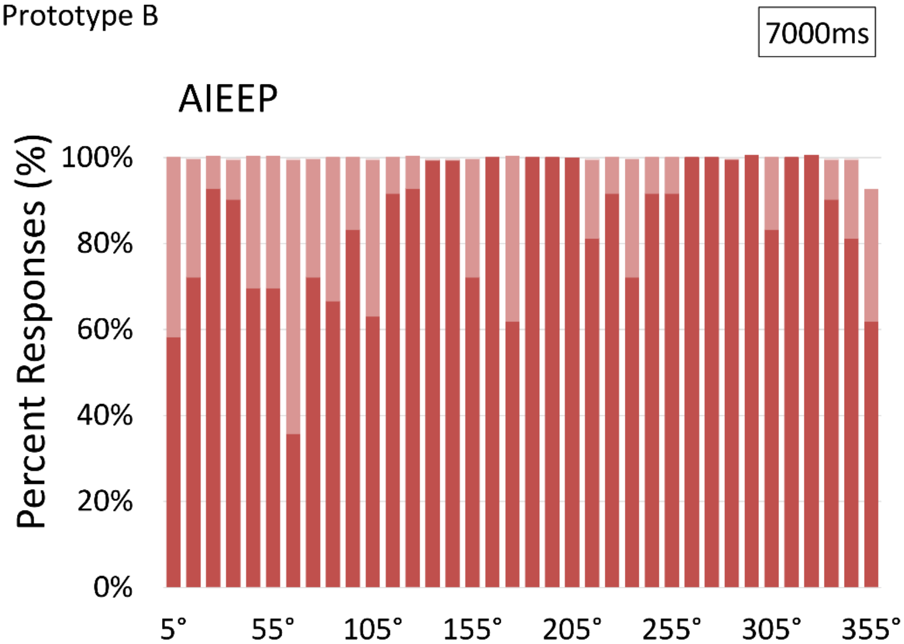

Fig. K-3 Proportion of responses to 7000-ms stimuli that were correct, were blurred, or a reversal, shown as a function of angle for the AIEEP trials: Prototype B only

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List of Symbols, Abbreviations, and Acronyms

AIEEP	Asymmetric Integrated Eye and Ear Protection
ANCOVA	analysis of variance
ANSI	American National Standards Institute
ARA	Applied Research Associates, Inc.
ASA	Acoustical Society of America
dBA	A-weighted decibels
dB HL	decibels relative to hearing level
dB SPL	decibels relative to absolute sound pressure level
DOD	Department of Defense
Gamma-IEEP	Gamma-Integrated Eye and Ear Protection
HCoE	Hearing Center of Excellence
HL	hearing level
HPD	hearing protection device
IEEP	Integrated Eye and Ear Protection
MAA	minimum discriminable audible angle
NSRDEC	Natick Soldier Research, Development and Engineering Center
TCAPS	tactical communications and protection systems

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2 DIR ARL
(PDF) IMAL HRA
RECORDS MGMT
RDRL DCL
TECH LIB

1 GOVT PRINTG OFC
(PDF) A MALHOTRA

5 US ARMY NATICK SOLDIER
(PDF) RSRCH DEV & ENGR CTR
M MARKEY
D COLANTO
A CHISHOLM
S GERMAIN
J KRUSZEWSKI

3 US ARMY AEROMEDICAL
(PDF) RSRCH LAB
W AHROON
E REEVES
H JONES

1 WALTER REED NATIONAL
(PDF) MILITARY MEDICAL CTR
D BRUNGART

1 AFRL RET
(PDF) R MCKINLEY

1 ARL RET
(PDF) T LETOWSKI

1 VIRGINIA TECH
(PDF) J CASALI

2 DOD HEARING CTR OF
(PDF) EXCELLENCE
T HAMMILL
K BUCHANAN

2 ARMY PUBLIC HEALTH
(PDF) CMND (PROVISIONAL)
M ROBINETTE
N VAUSE

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E THOMPSON
G ROMIGH
H GALLAGHER

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R WEATHERLESS
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