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Bone Conduction Headphone Research and Testing for xEMU Communications Applications

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The new space suit being developed for exploration EVAs on the surface of the Moon and in microgravity environments is referred to as xEMU. A government reference model has been developed and has undergone extensive functional and environmental testing. This suit contains new upgrades from the current EMU on ISS, such as integrated speakers and microphones, eliminating the need for astronauts to wear a Communications Carrier Assembly (CCA) on their heads during spacewalks. However, this design approach results in speaker-to-microphone acoustic coupling and communications echo and feedback.

A proposed solution to this issue is to replace the integrated open speakers with an astronaut-worn bone conduction headset for audio capabilities while on EVA to receive incoming voice communications from Mission Control and other EVA or IVA crew members. This would eliminate the acoustic coupling and echo effect since bone conduction technology transmits sound through purely haptic feedback. These earphones would also be more ergonomically sound than the current CCA.

A human-in-the-loop evaluation was performed, which compared five commercially available bone conduction headsets, evaluating comfort, fit, and adjustability for long-duration wear. Five engineering test subjects with different head sizes were utilized to wear the headsets for six-hour periods and provide succinct feedback and score the headsets on a variety of factors, in order to determine which of the headsets performed the best and were capable of advancing to future bone conduction audio testing.

Three of the headsets were well-received among the diverse group of subjects and could advance to further testing to be considered for future use under the xEMU helmet for exploration EVAs. Rating results and evaluation methods for this bone conduction headset evaluation will be presented.

Nomenclature

IVA = Intravehicular Activity
EVA = Extravehicular Activity
CCA = Communications Carrier Assembly
ISS = International Space Station
EMU = Extravehicular Mobility Unit
xEMU = Exploration Extravehicular Mobility Unit
xEVA = Exploration EVA
HITL = Human-In-The-Loop Test
MCC = Mission Control Center
NBL = Neutral Bouyancy Lab

I. Introduction

In order for an astronaut to communicate with the Mission Control Center (MCC), his/her assigned EVA (Extravehicular Activity) counterpart, or the IVA (Intravehicular Activity) crewmember inside ISS (International Space Station), he/she dons a Communications Carrier Assembly (CCA) on his/her head underneath the helmet of the Extravehicular Mobility Unit (EMU). The CCA is a cap that is fitted to the astronaut's head and includes dual microphones and left and right over-the-ear speakers which offer hearing protection and are used for incoming audio from multiple channels. Historically, the CCA has tended to be bulky, cause thermal discomfort, and leak sound if the chin strap was not pulled tightly enough to the chin, reducing the volume of incoming voice communications while creating outbound echo.

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Figure 1. Image of astronaut Jessica Meir wearing the CCA with the EMU at the NBL (Neutral Buoyancy Lab).[1]

The new spacesuit being developed for exploration capabilities, including Lunar EVAs, is called xEMU. NASA has developed a government reference suit design which incorporates integrated speakers and microphones inside the suit. This design eliminates the need for the crewmember to wear a CCA under the helmet. However, upon testing this technology, an issue was uncovered. With open speakers and microphones being situated inside the helmet volume, acoustic coupling occurred. This caused incoming audio to be picked up by the microphones, resulting in echo heard by the other participants on the EVA call. To resolve this issue, the Human Interfaces Branch (EV3) at Johnson Space Center has worked to incorporate a digital signal processor-based acoustic echo canceller to mitigate the echo. This effort has yet to be proven reliable in the various expected acoustic conditions inside the suit (such as varying static pressure, acoustic noise, and crew member head position) and meet suit speech intelligibility requirements.

Figure 2. Spacesuit engineer Kristine Davis modeling xEMU, standing beside NASA administrator Jim Bridenstine.[2]

As a back-up solution, bone conduction headphones were proposed to replace the bulky CCA and be used for incoming audio to transit sound void of any echo, while the embedded xEMU microphones would still be used to transmit speech from the astronaut inside the suit. Five commercial off-the-shelf (COTS) bone conduction headsets with different sized transducers were selected to be further researched to analyze their potential acceptability for future EVA use. Four of these headsets are wired, and one is a Bluetooth headset to use as a control group.

II. Bone Conduction Technology

Figure 3. Photo of NASA engineering test subject modeling Code Red Zero-M bone conduction headphones.

Bone conduction technology first gained popularity through its usefulness in military applications. Soldiers needed to listen in to radio transmissions while keeping the ear open to ambient noise on the battlefield. According to the authors Henry and Letowski in *Bone Conduction: Anatomy, Physiology, and Communication*, “Bone conduction is the process by which an acoustic signal vibrates the bones of the skull to stimulate the cochlea. Skull bone vibration can be a result of acoustic or mechanical stimulation of the skull.”

This occurs entirely separately from air conduction, in which the signal travels through the outer and middle ear to eventually arrive at the cochlea. This means that hearing protection can be worn on the battlefield to protect against loud noises from weaponry, while simultaneously taking in critical verbal communication through bone conduction. In audiology, bone conduction technology is used when fitting hearing aids in those with deformed or missing ear canals. Today, commercially available bone conduction headsets have slowly gained in traction to use for exercising and general day-to-day use.

During bone conduction transmission, the bones of the skull are set into motion. This in turn vibrates the left and right cochleae, that are surrounded in bone. These vibrations are translated into neural impulses that are perceived in the brain as sound. Because both cochleae are surrounded in bone, audio vibration occurring in any region of the skull will stimulate both ears with very little attenuation and miniscule time delays. Therefore, the time and intensity differences between the two cochleae during bone vibration are negligible for all the practical purposes.[3]

Shown below is a display of the pathways taken through the ear for both bone conduction and air conduction communications, or mechanical stimulation and acoustic stimulation, respectively.

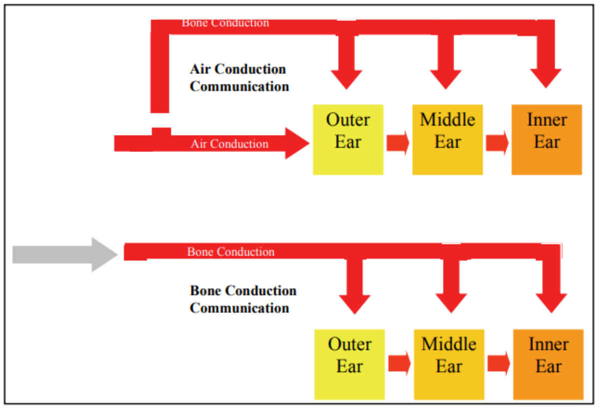


Figure 4. Diagram of pathways for bone conduction and air conduction through the ear.[3]

The figure displays fully separate pathways for each method, meaning mechanical (or vibrational) and acoustic stimulation can and do occur simultaneously.

In bone conduction transmission, vibrator size, placement, and applied static force can all affect the amount of energy transmitted through the bones. This will affect the sound perceived by the listener. Bone conduction transmission is more effective when the signal is transmitted through a vibrator placed on the human head (or teeth) over an airborne sound wave striking the skull. For non-clinical applications, the ideal location for the vibrator is on the side of the head. The precise location is called the condyle, and this is where stimulation is in line with the movement of the ossicular chain. The static force for bone conduction transmission should be great enough for sound to be adequately heard, but not so much that the force causes discomfort to the listeners from the vibrations. This optimal static force value tends to be around 4.9 N. To achieve the greatest audio sensitivity in both air and bone conduction sounds, frequency range should be near the mid-frequencies, around 1 kilohertz.[3]

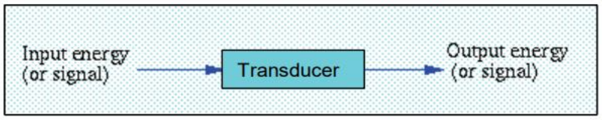


Figure 5. This demonstrates the energy conversion using a transducer.[3]

The electromechanical operation of bone vibrators is similar to that of air conduction transducers (e.g. loudspeakers or headphones), except for the difference in the magnitude of impedance of the medium facing the transducer. Sound from loudspeakers passing through free space has the impedance of about 400 $\mathrm{N \cdot s/m^3}$. The impedance of the skull/head structures is several thousand times greater. Mechanical impedance of the surface skin at the head ranges between 30 and 50 dB re 1 N·s/m.

The impedance of both the transducer and the head structure should match to provide effective transmission of energy between the two. Due to this, bone vibrators require a much higher impedance than earphones or loudspeakers, making hard surface transducers a lot more effective than soft surface transducers for bone conduction transmission. There are two methods used to calibrate bone conduction vibrators. The first is through using human listeners to test subjectively, and the second is an objective test through measurement on an artificial mastoid. Using the latter, by taking a measurement of the frequency response of the bone conduction vibrators, an objective view of the function of the device can be produced. When directly comparing multiple bone conduction devices, caution should be taken, as differences in head shape and size can contribute to differences in the measured responses.[3]

III. Designing a Comfort and Fit Test

The first step in determining whether bone conduction headsets are feasible for xEVAs was to (1) determine if they would stay on the head during the course of an eight-hour EVA and (2) evaluate comfort of the headsets for long-term wear. A human-in-the-loop test (HITL) was designed to gauge these metrics.

For this comfort and fit analysis, five anthropometrically diverse test subjects were chosen to wear and rate each of the five headsets. The engineering test subjects consisted of three males and two females, two subjects of whom wore glasses (one male, one female), all of whom fell into three distinct head breadth/circumference groups.

Four of the bone conduction headsets that were used in this HITL are wired. These headphone models are Code Red Battle Zero-M, Motorola RMN5114A, Motorola PMLN4585A and Motorola RMN5048B. One Bluetooth headset, the Shokz OpenComm headset, was also evaluated. Even though Bluetooth technology is not an option for selection due to the risk of batteries dying during a long duration, eight-hour Lunar EVA, the lightweight nature of the headset made it an ideal “control group” for this test.

IV. Procedure

Test subjects wore each headset for six hours. This length of time was selected as it is similar to the duration of a full Lunar EVA, eight hours, but was short enough to fit within the duration of the work day with flexible start/stop times based on participants' respective work schedules and other meetings.

Because the core metrics being evaluated in this test were comfort, fit, and adjustability, it was not necessary for the test day procedure to include outlined tasks for the subjects to perform. Rather, the instructions given were to perform nominal day-to-day tasks, provided those tasks were not too physically demanding such that they could incur unnecessary slippage of the headset being worn. The headsets were evaluated for stability, i.e. how well they stayed on the head and did not shift on their own or fall off the head entirely; however; it was necessary that the tasks being performed by the subject were not more intense than what would be performed during EVAs. Additionally, an outlined list of "Dos" and "Don'ts" was created for the test subjects to adhere to. One example was, "Don't adjust the headphones, when possible," because the astronaut out on EVA would be wearing a helmet over the headphones, and thus unable to readjust during that eight-hour length of time. This list given to the test subjects allowed for more credible and accurate results.

The testing location was wherever the participants normally do their work, either in their remote work environment or at their desk at Johnson Space Center. There were five test days total, so that each of the subjects could wear and evaluate all five headsets. Nobody wore the same headset on a given test day, which was done to prevent a bias in the results, since the first test day could have slightly lower questionnaire ratings than consecutive test days due to the newness of wearing a foreign object on the head for a large portion of the day, causing extra perceived discomfort.

Subjects were evaluated via verbal and written questionnaires at three distinct points in the test day. The verbal questionnaire was a fifteen-minute Teams video conference and asked questions relevant to the intensity of pressure or pain felt on the skull from the headset. Depending on the subject's answers to those questions, he/she would potentially remove the headset prior to the end of the test day. However, participants were permitted to remove the headset early at any point in the day if it became too uncomfortable. The brief verbal questionnaires/check-ins happened (1) shortly after the subject had donned the headset, (2) mid-test day, at the three-hour mark, and (3) at the end of the test day, at the six-hour mark.

Questions that were more detailed and specific were asked via a written questionnaire which was divided into three parts and completed after each of the verbal questionnaires. These questions targeted a few different metrics as criteria used to determine which headsets were deemed superior and would move on to further testing.

The first is **Fit/Adjustability**, which is defined as how secure the headset fits on the head, whether it is adjustable to accommodate different head sizes, and how well it stays on over many hours (since crew would not be able to adjust the headsets during an 8hr EVA). The second is **Pressure/Pinch**, which is how forcefully one or more parts of the headset pushes on the skull. If there are pinch points that apply significant pressure to the head, it can distract crew from EVA tasks or even cause a headache. The third metric is **Comfort/Noticeability**, which encompasses the weight of the headset and other factors of comfort outside of specific pinch points, like how noticeable or bothersome the headset feels over time, and how restrictive the headset is to head movements and other activities. Finally, included was the **Overall** rating, which is a rating subjects provided at the end of the test that includes all the considerations above.

Questions asked in the verbal and written questionnaires were a combination of open response, numerical ratings, and "Yes/No" paired with an explanation. Many of these questions were asked at the start, middle, and end of the test day to see how the test subjects' perception of headset comfort and fit changed overtime.

V. Results

In discussing the results of how the headsets performed, each model will be referred to by its assigned number in the image below. For example, the Shokz Bluetooth Wireless bone conduction headset, the control group in this HITL, will be referred to as "Headset 5" in this section.

Code Red Battle Zero-M (1) | Motorola RMN5114A (2) | Motorola PMLN4585A (3) | Motorola RMN5048B (4) | Shokz Bluetooth Wireless (5)

Figure 6. Headsets 1 through 5. Each subject wore every one of these five headsets for six hours at a time on each test day, until all five subjects had worn and rated all five headsets.

A. Protrusion

Before the first test day, participants met in-person to be measured in each headset. The measurement taken was the horizontal distance in inches from the nape of the neck to the farthest point to which the headset protruded out behind the head. This was done to gauge potential geometric interference with the back of the xEMU helmet. The headset that protruded the most was Headset 3, with an average protrusion of 1.62 inches. A headset that sticks out this much will likely interfere with the back of the helmet, either when the head is level at rest or while tilting or turning the head while performing EVA procedures. The headsets which protruded the least are Headsets 2 and 4 with average measurements of 0.32 in and 0.05 in, respectively.

B. Fit/Adjustability

Subjects were asked about the difficulty in donning each of the headsets since crew members would be required to easily put on and adjust the headset in a timely manner during EVA prep. Subjects generally noted all headsets being simple and intuitive to apply to the head and arrange/adjust into the correct configuration. Subjects with glasses noticed interference with Headsets 1 and 4. One subject could not wear his glasses with Headset 4. He noted that he would be able to wear them if modifications were made to the EVA glasses or if a band or external component could attach to the glasses to secure them to the headset. Subjects with long hair were allowed to tie their hair back in a style of their choosing that would not interfere with the headset, since no current ISS rule or regulation exists for how long hair is to be pulled back and tucked away. For the two long-haired subjects, one wore her hair in a low ponytail for all test days, and the other wore her hair in a low braid. For the band that wraps around the back of the head, these test subjects chose to wear their hair under the band during all test days.

For adjustability, Headsets 1, 3, and 4 can be adjusted to fit different head sizes, with Headset 4 containing multiple adjustment features. Headsets 2 and 5 are not adjustable, yet test subjects felt that these two headsets were secure and did not need to be readjusted during the test day. They felt the same regarding Headset 4. Headsets 1 and 3, however, did require readjustment from a couple of the participants.

Subjects were asked their opinion on how secure the headsets felt on their heads. This includes considerations for how well it fits, feels, and stays on throughout the test day, to give an overall numerical rating to this test metric. Responses can be seen in the table below.

	Headset 1	Headset 2	Headset 3	Headset 4	Headset 5
S1*	4, 4	4, 5	5, 5	5, 5	4, 5
S2	1, 1	5, 5	5, 5	5, 4	4, 5
S3	3, 3	3, 4	3[‡], 3	5, 5	3, 4
S4	4, 4	4, 5	5, 4	5, 5	5, 5
S5*	5, [†]	5, 4	4, 4	4, 4	5, 4

[†] No answer; headset was removed early.

[‡] Secure but noted that if the back piece contacted anything, it would move.

Figure 7. Subject responses to "Score how the headset feels on your head", on a scale of 1 to 5, (poor to exceptional). The score before the comma is from 3 hours into the test day; the score after the comma is from the end of the test.

Legend

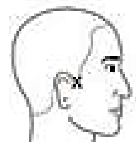
***** (asterisk): glasses
Group 1: middle percentile head size
Group 2: upper percentile head size
Group 3: above upper limit head size

The first number in each cell represents the score assigned at the three-hour mark, and the second represents the score given at the six-hour mark. The second number is weighted more heavily than the first, since that is how secure the headset felt at the end of the entire test day. Headsets 2, 4, and 5 are tied for first when looking at only the second number. This aligns with subject feedback via comments received on this metric as well.

C. Pressure/Pinch

Subjects were asked in each of the questionnaires to identify any areas of pressure on their head, i.e. pinch points, and to describe the intensity of this pressure or pain experienced, if any. Below is a synthesized version of the responses. It includes an average among subjects of the location(s) on the skull where pressure or pinch was experienced, as well as high-level subject comments/feedback.

Headset 1:

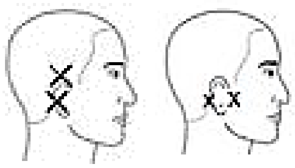


S1: Negligible pinch/pain.
S2: Constant slipping of earpiece which moved to cover the ear.
S3 & S4: Pinching in front of the ear.
S5: Significant pain in front of the ear; rendered early removal of headset.

Headset 2:

S1, S3, S5: Pinch point at front of ears where bone conduction speaker sits.
S2, S4: Negligible pain/pinch.

Headset 3:

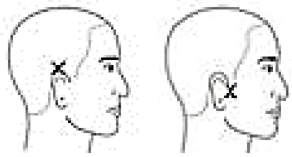


Pinch point at front, back, and above the ears noted by subjects.
S1-S5: Reported some area of uncomfortable pressure.

Headset 4:

S1, S4: Slight pinch in front of ears.
S3: Headache 2hrs into test from pressure in front of ears; removed early.
S2, S5: Negligible pain/pinch.

Headset 5:

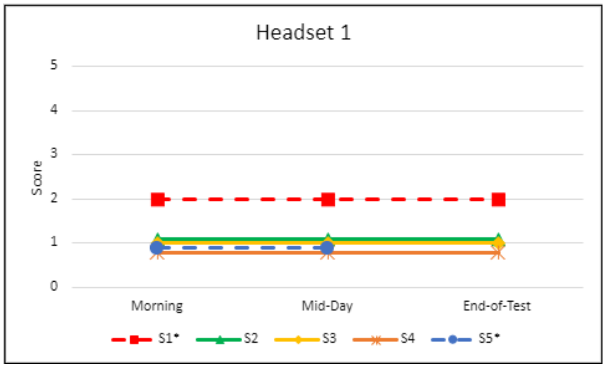


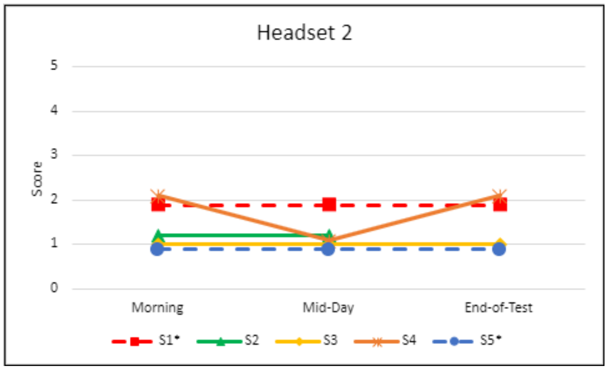
S1, S5: mild pinch at top of ears
S2, S3, S4: negligible pain/pinch

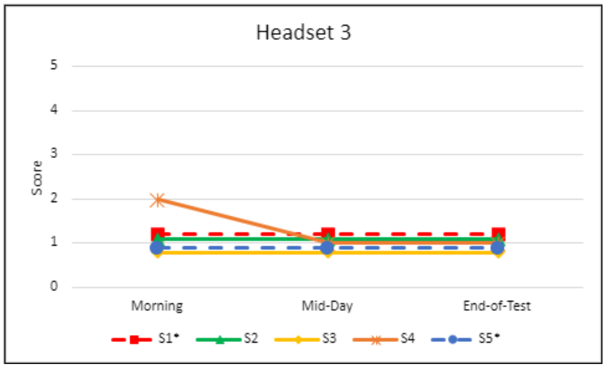
In analyzing pressure/pinch markings and subject feedback, Headset 3 has the highest number of pinch points common among multiple test subjects, and all of them collectively experienced some level of discomfort. Headset 5 results and feedback displays the lowest level of pinch or pain experienced among subjects out of all the headsets. Headsets 1 and 4 were removed early by one test subject (different test subject each time) due to discomfort.

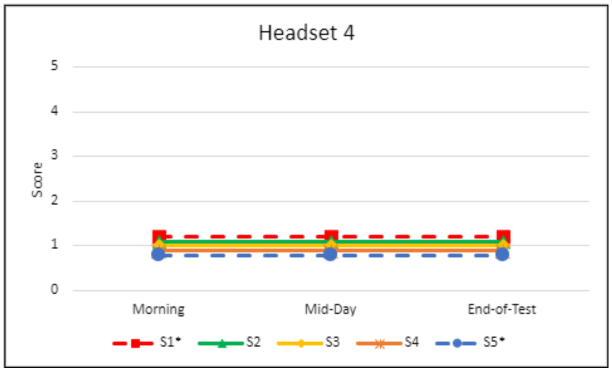
Subjects were also asked to rate the pressure applied to the back of the neck, on a scale of 1 to 5 (low-high). Responses from all subjects for each of the headsets are given at the start of the test, at the halfway point, and at the end of the test.

Ratings of Pressure Applied to Back of the Head/Neck









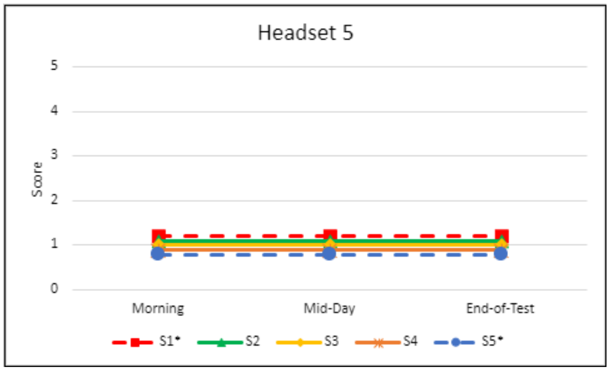


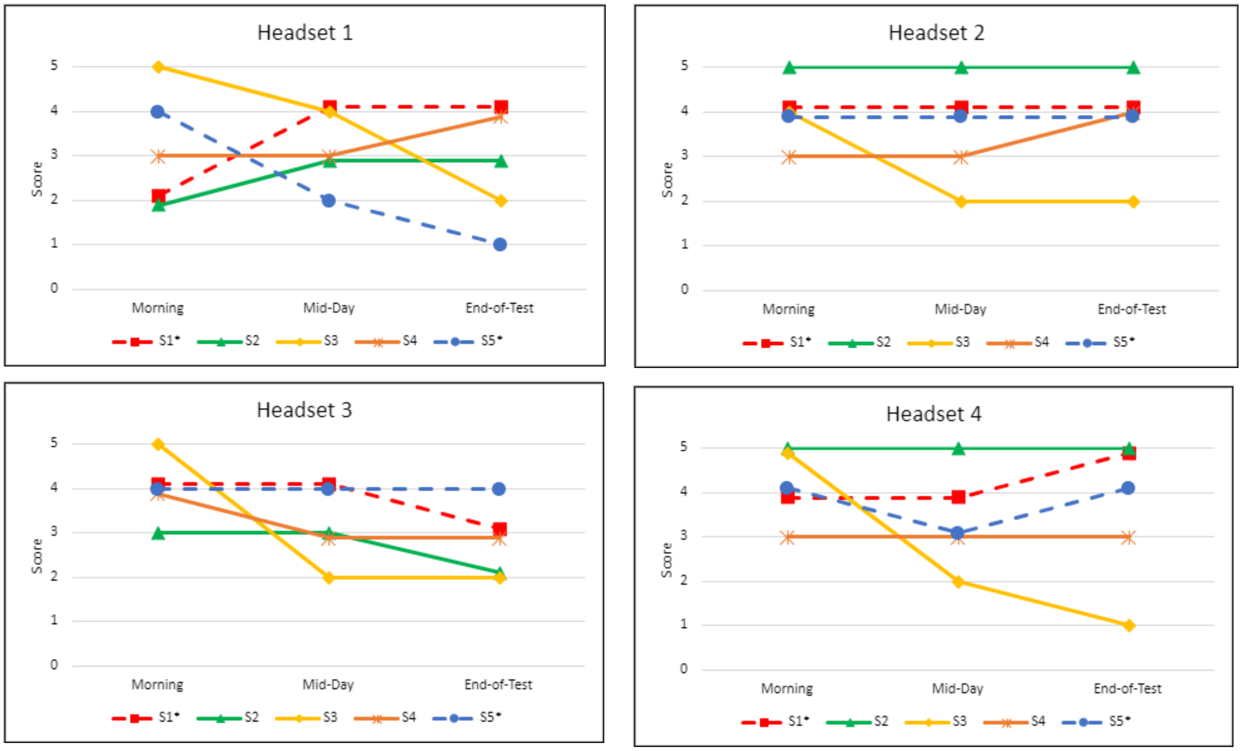
Figure 8. Ratings on a scale from 1 to 5 of how much pressure was felt on the back of the head and neck.

Generally little to no pressure was felt on the neck and back of the head, but Headsets 1 and 2 had scores that exceeded 1 by the end of the test day.

D. Comfort/Noticability

Subjects were asked to rate the overall perception of comfort of each headset on a scale of 1 to 5, 1 being the least comfortable, and 5 being the most comfortable. These ratings can be seen below as well as changes in the perception of comfort throughout the test duration.

Ratings of Perception of Comfort



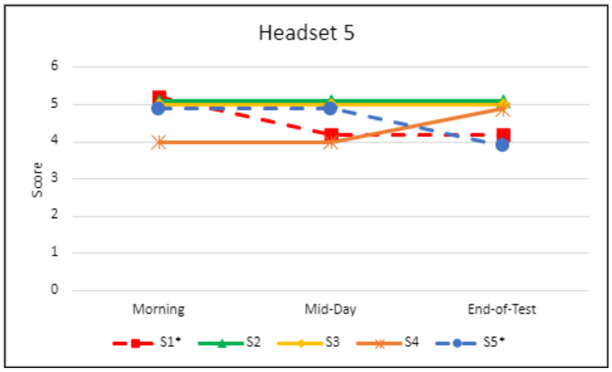


Figure 9. Ratings on a scale from 1 to 5 of how comfortable each headset was.

Headset 5 achieved scores of 4 and 5 among all subjects, making it rated the highest for perception of comfort. Neither Headsets 1 nor 3 received any scores of 5, and Headsets 2 and 4 received a wide range of scores among participants.

Additionally, subjects were asked about how the weight of each headset affected comfort. On a scale of 1 to 5 (low-high), they were asked how heavy the headset feels on their head. These results appear below.

Ratings of How Heavy each Headset Felt on the Skull

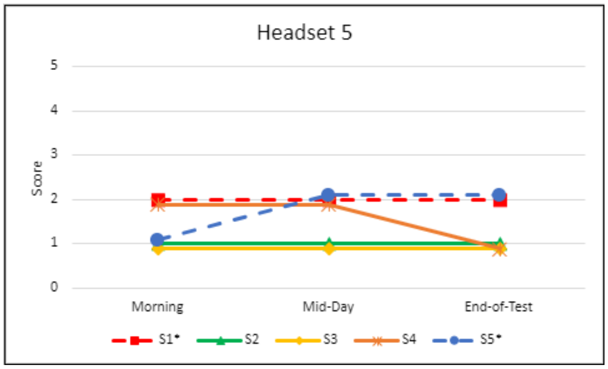
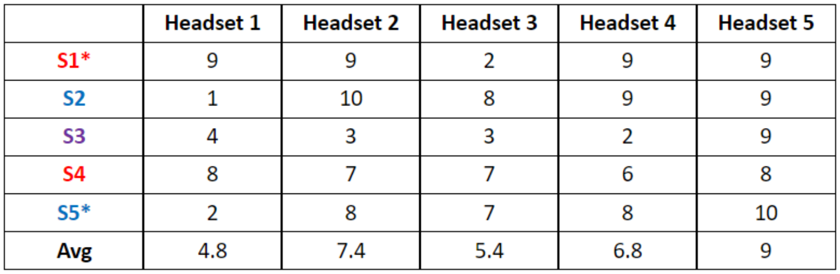


Figure 10.Ratings of weight perception of each headset applied to the head/ skull, on a scale of 1 to 5, one meaning the headset feels lightweight and unnoticeable, 5 meaning it feels very heavy and uncomfortable.

Headset 4 had the highest scores, meaning its weight was most noticeable among subjects out of all five headsets. It is the heaviest headset with the most structure to it, and it includes an overhead strap. Headset 5 felt the lightest among subjects, likely due to it being wireless. Some complaints from subjects during the test were that the weight felt was produced by the tug of the heavy amplifier attached to the wire, not the headset itself. This wouldn't be an issue in EVA applications, as this component would be attached to the suit and configured in a way such that it does not cause tugging on the headset.

E. Overall

The final question posed on each test day asked for an overall rating, taking into account each subject's entire experience of wearing the headset for six hours. The table below lists Subjects 1 through 5 ratings for Headsets 1 to 5, with average scores shown in the last row.



	Headset 1	Headset 2	Headset 3	Headset 4	Headset 5
S1*	9	9	2	9	9
S2	1	10	8	9	9
S3	4	3	3	2	9
S4	8	7	7	6	8
S5*	2	8	7	8	10
Avg	4.8	7.4	5.4	6.8	9

Figure 11. Overall scores rated on a scale of 1 to 10 (low-high), for Headsets 1 through 5 by Subjects 1 through 5. Refer to Legend for S1-S5 denotations.

Headset 5 had the highest overall ratings, and Headsets 1 and 3 had the lowest.

In collecting and reviewing subject feedback, both quantitative and qualitive, summarized average inputs can be determined, which are provided below.

Headset 1: Removed early by one subject wearing glasses, received low ratings due to headset discomfort, not well-received by most subjects.

Headset 2: Rated to be second most comfortable and relatively secure, although no adjustability features in this headset, does not stick out much from the head/neck.

Headset 3: Band sticks out so far behind the head that it would most likely be an issue, pinch points reported from all subjects and at multiple regions on the head.

Headset 4: Felt most secure and has least potential interference with back of the helmet, subject with the largest head breadth/circumference needed to remove early; also glasses worn on EVA would need to be configured to be compatible with the headset.

Headset 5: Overall favorite among subjects, lightweight and comfortable, secure, band may or may not be an issue.

Combining feedback and rankings, Headset 5 was deemed as the top contender. However, for it to be used for EVAs, it would need to be redesigned to be wired instead of wireless. Headset 2 had the second-best ratings. There were a few complaints from subjects, but the numerical ratings show that the headset is comfortable and secure. Headset 4 could be an issue for crew members with greater head breadth or those who choose to wear glasses while on EVA, but the overhead strap makes this model the most secure and this headset protruded the least. These factors make Headset 4 another potential option for future consideration.

VI. Design Considerations

Upon completing the comfort and fit HITL, it was determined that bone conduction headphones and technology could be a viable option for future xEVA applications. Further research and testing would be required, but based on long-term wear alone, multiple bone conduction headsets appeared to be adequately adjustable, secure, and comfortable, and acceptable for further consideration.

An open question remains concerning the acoustic environment of the xEMU, which is still in development. It is possible that acoustic noise generated by suit fans and pumps may be at levels that result in the need for the crew to have over-the-ear hearing protection while out on the eight-hour EVA. Over-ear coverings would interfere with the placement of bone conduction transducers. One potential solution is to embed bone conduction transducers into over-ear hearing protection earpads. They would be placed near the portion of the earpad that rests on the cheek bone in front of the ear, such that bone conduction technology will still work. Then, those over-ear pads could be integrated into the lightweight geometry of the bone conduction headset to create a new, lightweight, hybrid bone conduction/traditional headset.

At this stage, that solution is simply a concept, and a prototype would need to be engineered and tested to see if this option would work. A potential drawback to this idea is that the heaviness of the headphone pads might not work with the lightweight surrounding geometry which wraps around behind the head, resulting in too much downward tug on the tops of the ears. Another challenge might be securing the new engineered hybrid headset to be tight enough for the bone conduction technology to produce enough amplification of sound. Embedding transducers inside of soft, flexible cushioning may result in dampened vibrations, therefore decreasing the audio quality and sound being produced. Unless the headset is pushing very tightly against the skull, the technology may not work in this configuration. Even if it does work well, the tightness could create discomfort, rendering bone conduction headphones to be ill-suited for xEVA communication.

VII. Forward Work

Further efforts of solving the hearing protection issue will be done as well as future testing of the most highly rated bone conduction headphones from the HITL. This will include speech intelligibility testing to confirm that bone conduction transducers integrated into over-ear hearing protection can provide performance that will meet the 90%-word identification accuracy requirement. Aspects such as potential for vertigo and headaches as a result of consistent skull bone vibrations from the headphone transducers should also be studied when testing bone conduction headphones for their audio capabilities. Other future testing to be conducted, if a feasible approach to bone conduction earphones can be developed, will involve astronauts as test subjects. They will perform certain EVA tasks while wearing a bone conduction headset under an xEMU helmet in the NBL and practice communicating with another crew test subject in a simulated EVA. This future HITL will additionally serve as a more robust way to test headset fit and stability, since the suited crew member will not be able to adjust the headphones, consciously or unconsciously.

VIII. Conclusion

Bone conduction technology might have suitable EVA applications to work with xEMU for incoming audio from Mission Control and from IVA and EVA crew members. COTS bone conduction headsets were tested in a long duration comfort and fit analysis with human test subjects. These ratings eliminated the specific headset styles which would not be suitable to wear on EVA, but overall proved that bone conduction headphones can be worn comfortably for several hours and fit securely on a range of head sizes. Future testing will be done to answer open questions and address any comfort and performance issues discovered in early development. Research will be conducted to see what other options exist, and new designs might emerge from blending COTS components with NASA engineering.

Acknowledgments

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