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# SQUAD-LEVEL OPERATIONAL PERFORMANCE UNDER VARYING HEARING PROTECTION DEVICES AND SIMULATED HEARING LOSS

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## ABSTRACT

Noise-induced hearing loss continues to be an issue for military personnel, who rely on their hearing to maintain situational awareness and maximize operational effectiveness. Methodological advancements in measuring performance in dismounted combat are paving the way to examine the impact of hearing in these complex environments. In this study, squads from the US Army's 4th Infantry Division conducted standard combat training exercises under different hearing conditions using hearing protection devices (HPDs; passive, active) and hearing loss simulation (normal hearing, moderate-to-severe loss) while outfitted with audiovisual recorders, GPS trackers, laser engagement systems and inertial measurement units on the helmet and weapon. This allowed all squad movement, communication, and engagements to be captured. In addition, performance ratings were collected from observer-controllers (OCs) and participating Soldiers after each drill. Results show a clear advantage of active HPDs compared to the other conditions tested for both Soldier and OC ratings of squad performance. Soldiers also reported low frustration while wearing active HPDs and suffered less casualties on average, whereas a moderate-to-severe hearing loss resulted in higher mental demand and frustration and the highest number of casualties incurred. These findings can help inform Military leaders of the importance of wearing effective hearing protection in combat.

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## 1. INTRODUCTION

A Warfighter's hearing is critical for combat effectiveness, particularly in dismounted combat operations where Soldiers rely on their hearing to detect enemy movements, identify threats, and coordinate with their unit. In environments with limited visibility, such as dense forests or urban battlefields, auditory cues like distant gunfire, footsteps, or radio transmissions provide critical information for survival. The ability to process these sounds quickly allows soldiers to react effectively, enhancing their situational awareness (SA) and tactical decision-making.

Unfortunately, the battlefield is also filled with hazardous noise (e.g. explosions, gunfire, aircraft, vehicle engines) that can cause temporary or permanent hearing damage (e.g. hearing loss, tinnitus) and auditory fatigue. Even brief exposure to these sounds without protection can impair a soldier's ability to detect threats, potentially reducing combat effectiveness in both the short and long term.

Despite these risks, many soldiers are reluctant to wear traditional hearing protection because they fear it will diminish their SA. Standard passive earplugs or earmuffs can muffle critical battlefield sounds, making it harder to detect enemy movements or communicate effectively with teammates. In high-stakes combat situations, soldiers may prioritize immediate survival and effectiveness over long-term health, leading them to forgo hearing protection altogether.

To address this challenge, advanced HPDs have been developed that can both safeguard hearing and enhance communication [1]. Modern tactical headsets and electronic earplugs filter out harmful noise levels while amplifying essential sounds, such as voices and quiet enemy movements. These devices can allow soldiers to maintain SA without sacrificing their hearing health. Ultimately, Soldiers must balance the tradeoff between hearing protection and SA. While advanced devices offer significant improvements, they are not always available or practical in every situation. Troops often have to decide whether to risk hearing damage for enhanced SA or rely on protection that may slightly reduce their ability to perceive battlefield cues. As technology continues to evolve, finding the optimal balance between hearing safety and operational effectiveness remains a crucial challenge for modern militaries.

In battlefield environments, degraded hearing can occur as a result of hearing protector use, but it can also occur as a result of acute hearing impairment from unprotected exposures during the current engagement or chronic hearing loss from a lifetime of noise exposure prior to the current engagement. In order to make decisions about when, how, and what kind of hearing protection to wear in combat, and also about who might have an acute or chronic hearing loss that is severe enough to interfere with combat operations, it would be extremely helpful to collect information that might allow a prediction of the impacts that different levels of hearing impairment might have on operational performance, regardless of the source.

Traditionally, testing the impacts of hearing loss or HPDs on combat operations has been limited to laboratory measures or carefully controlled field studies that focus on isolated tasks. However, the battlefield is a dynamic environment and the factors that influence combat effectiveness are extremely complex, so it has been difficult to translate these findings to lethality, survivability, or mission success in actual operational environments. Some studies have begun to examine the impact of hearing acuity on combat performance in more comprehensive environments using simulated sound sources [2] or realistic sound sources combined with hearing loss simulation [3-5]. However, in the infantry realm, this has been limited to the individual or fire team level, whereas the fundamental fighting element is the infantry squad.

Beyond logistical considerations, one challenge of expanding to the squad-level has been the lack of validated measures of operational performance in dismounted combat. Thankfully, recent methodological advancements in measuring performance in these environments [6-7] provide a framework to now explore the impact of hearing acuity at the squad level. Interestingly, the initial findings from those studies indicate that the most important contributing factor to combat performance is effective communication within the squad, further emphasizing the need to better understand this issue [7].

In the present study, we utilized the methodologies mentioned above for measuring/analyzing squad performance while varying each squad's hearing acuity across drills using hearing loss simulators and HPDs to examine their impact on performance, providing critical information for our Warfighters.

## 2. MATERIALS AND METHODS

### 2.1 Combat Exercise

The combat exercise used for the study was closely modeled after Battle Drill 2A: Conduct a Squad Assault, which is a fundamental infantry exercise that trains soldiers to close upon and destroy an enemy position through coordinated fire and movement. The drill involves a squad maneuvering against an opposition force (OPFOR), typically starting with suppressive fire to fix the enemy in place while an assaulting element moves forward to secure an objective. Soldiers execute bounding movements, alternating between providing covering fire and advancing under protection. The exercise emphasizes teamwork, communication, and aggressive action to overwhelm the enemy.

Data collection took place at a designated training area in Ft. Carson, CO consisting of primarily wooded terrain and grassland with slight elevation changes incorporating hills, meadows, and gulches. There were two Situational Training Exercise (STX) lanes setup on the range, each with differing movements toward their objective. In both cases, the primary objective was to secure a bunker manned by two members of the OPFOR. A third OPFOR member served as a Listening Post/Observation Post (LPOP) a few hundred yards forward of the bunker, where he was concealed in the brush to provide a surprise attack element. Each member of the OPFOR was outfitted with an M4 Carbine rifle.

### 2.2 Participants and Squad Composition

A total of 86 Soldiers, all male, aged 18-34 years, were recruited from the US Army's 4th Infantry Division to participate as part of their Squad Table III training program. They ranged in rank from E-1 to E-6 and were assigned to remain within their normal squad and role for the duration of the exercises. Each 9 to 11-man squad consisted of a Squad Leader, a two-man gun team (Gunner and Assistant Gunner), and two fire teams (Alpha and Bravo). Each fire team consisted of 3-4 members depending on the squad size. Each had a Fire Team Leader, an Automatic Rifleman, and either a Grenadier or Rifleman (or in some cases both). The Gunner was outfitted with an M240 machine gun, the Automatic Rifleman with an M249 SAW (Squad Automatic Weapon), and the Grenadier with an M203 grenade launcher mounted on an M4 Carbine rifle. All other squad positions carried M4 Carbine rifles and all weapons were loaded with blank ammunition.

**Table 1.** Audiogram used for the Simulated Hearing Loss Condition.

| Frequency (kHz) | 0.25 | 0.5 | 1 | 2 | 4 | 8 |
|---|---|---|---|---|---|---|
| Level (dB) | 50 | 50 | 55 | 65 | 85 | 95 |

### 2.3 Hearing Conditions

Four hearing conditions were tested in the study, including two HPD conditions and two hearing simulation conditions. The active HPD (Peltor condition) tested was the Peltor ComTac XIII (3M Corp.), which encompasses downleads for participants outfitted with radio communications (Squad Leader and Fire Team Leaders). The other HPD tested was a standard foam earplug (Foam condition), which differed depending on the size for each participant, as determined by an audiologist (3M EAR Classic SuperFit 30 and 33 for small and large, respectively, and Sound Guard 2-color for medium). The two hearing simulation conditions were administered via a custom-designed helmet-mounted hearing loss simulator known as the HL Sims (Sensimetrics Corp.). The HL uses earphones outfitted with small microphones to pass through sound unfiltered when in the normal hearing setting (Simulated Open Ear condition). To simulate hearing loss, a combination of attenuation from the earplug and additive masking noise elevates the detection thresholds at certain frequencies, depending on the audiogram simulated (see [5] for more details). For this study, we chose a moderate-to-severe hearing loss using the values shown in Tab. 1 (Simulated Hearing Loss condition). The Simulated Open Ear condition served as a stand-in control condition since operating with a truly open ear would put the participants at risk of hearing damage from weapons fire.

### 2.4 Additional Equipment and Measurements

In addition to donning hearing loss simulators and HPDs, participants were outfitted with digital audio recorders (Evida Corp.) and GoPro cameras (GoPro, Inc) to capture communication. Soldiers' helmets and weapons were also equipped with inertial measurement units (IMUs; ADPM, Inc) to track acceleration, angular movement, and orientation of the head and weapon, and to count the number of rounds fired by each participant. Their weapons were also equipped with the Instrumentable-Multiple Integrated Laser Engagement System (I-MILES) lasers and they wore vests and halos with I-MILES sensors. Fig. 1 shows an example of a fully-equipped Soldier.

**Figure 1**. Fully equipped Soldier with red circles highlighting from left to right: helmet IMU, audio recorder mounted on the HL Sim, GoPro, and weapon IMU.

I-MILES data were routed to a central control tower using a body worn radio frequency transmitter that doubled as a Global Positioning System (GPS) tracker as part of the Homestation Instrumentation Training System. This system allows all movement and engagements to be captured for visualization in real time and to be saved for after action reporting and data analysis (Fig. 2).

### 2.5 Procedures

In total, there were six squads that each ran through four drills of the exercise alternating between the two STX lanes (two drills per lane) for a total of 24 drills. Each drill was conducted with all squad members in one of the four hearing conditions and conditions were switched between drills to achieve a balance within each squad.


**Figure 2**. Homestation Instrumentation Training System screenshot showing Bravo team engaging with OPFOR while Alpha team flanks left to assault. The red line indicates a pairing line between the OPFOR and Gunner and the red hat indicates the OPFOR as the shooter. The LPOP can be seen in the bottom left corner.

Before the start of the exercise, participants completed a hearing exam and filled out an intake questionnaire about their demographics, military and combat history, and experience using HPDs. They were also fit with appropriately-sized hearing protection and trained on how to operate the Peltors. After each drill, Soldiers rated their own performance and communication ability and completed the NASA Taskload Index (TLX) [8] via a tablet PC running a custom TabSINT [9] protocol. In addition, unit commanders (Platoon and Company) acted as OCs throughout the exercise and provided ratings of squad performance on two scales assessing Battle Drill task steps and tactical performance principles

### 2.6 Data Analysis

#### *2.6.1 Observer-Controller Ratings*

OC ratings were modeled using linear mixed effects regression in R version 4.4.1 [10]; the buildmer package version 2.11 [11] was used for model selection, using backwards selection and likelihood ratio testing to compare nested models; the effects package was used for visualization of model fitted values. The maximal fixed effects structure evaluated included two-way interactions between condition and each of the following squad-level measures: drill number (4 levels), mean years of service among squad members, mean length of time since the most recent live fire event, the mode value for length of time with the current squad, and mode value for the number of squad leaders during their current assignments, as well as non-interacting fixed effects of platoon (3 levels), lane (2 levels), and mean squad member age (continuous). The maximal random effects structure evaluated included interacting by-OC intercepts and slopes for condition and lane, as well as a random intercept of drill.

#### *2.6.2 NASA Taskload Index*

Responses to the NASA TLX were modeled using linear mixed effects regression using the methods described in the above section. The maximal fixed effects structure evaluated included an interaction of TLX subscale (categorical; 6 levels) and condition (categorical; 4 levels), along with non-interacting fixed effects of drill number (categorical; 4 levels), number of years of military service (continuous), age (continuous), and duration of time since the most recent live fire event (continuous). The maximum random effects structure evaluated included by-participant intercepts and slopes for condition and drill number, as well as a random intercept of date.

## 3. RESULTS

### 3.1 Observer-Controller Ratings

The final model selected included non-interacting main effects of condition and drill number, as well as a random intercept of OC grader. The main effect of condition is visualized in Fig. 3 and shows that performance was consistently rated higher when squad members were in the Peltor condition as compared to the Foam plugs ($b$=-12.56, SE=4.89, $t$=-2.57, $p$=.01) and Simulated Hearing Loss conditions ($b$=-19.2, SE=5.26, $t$=-3.65, $p$=.001). OC ratings did not differ significantly between Peltor and Simulated Open Ear conditions ($b$=-10.13, SE=5.2, $t$=-1.95, $p$=.06).

The non-interacting fixed effect of drill number indicates a pattern of improved ratings over the course of four drills. Ratings for Drill 4 were significantly higher than those for Drill 1 ($b$=17.7, SE=5.07, $t$=3.49, $p$=.001) and Drill 2 ($b$=11.97, SE=4.87, t=2.46, $p$=.02). Ratings did not differ between Drills 1 and 2 ($b$=5.73, SE=4.89, *t*=1.17, *p*=.25) nor between Drills 3 and 4 (*b*=4.41, SE=5.12, *t*=-.86, *p*=.39).

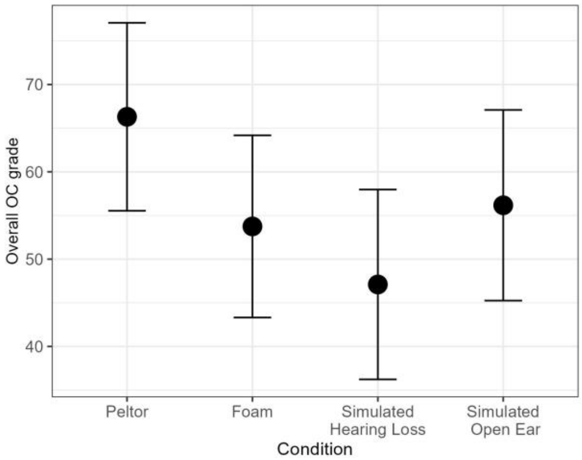


**Figure 3**. Model-fitted values for OC grade visualized as a function of hearing condition. Error bars reflect the 95% confidence interval. Higher values reflect better performance.

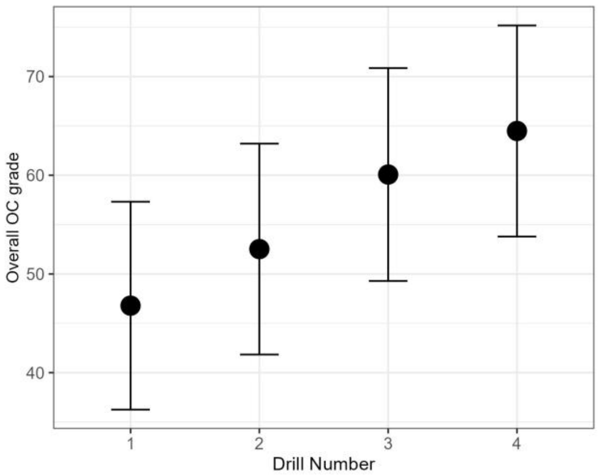


**Figure 4**. Model-fitted values for OC grade visualized as a function of hearing condition. Error bars reflect the 95% confidence interval. Higher values reflect better performance.

### 3.2 NASA Taskload Index

The final model selected to describe the NASA TLX data included an interaction of TLX subscale and condition, a non-interacting fixed effect of age, and a by-participant slope and intercept of condition. Significant interactions were examined by re-leveling and re-fitting the model to obtain estimates at all levels; see Fig 5.

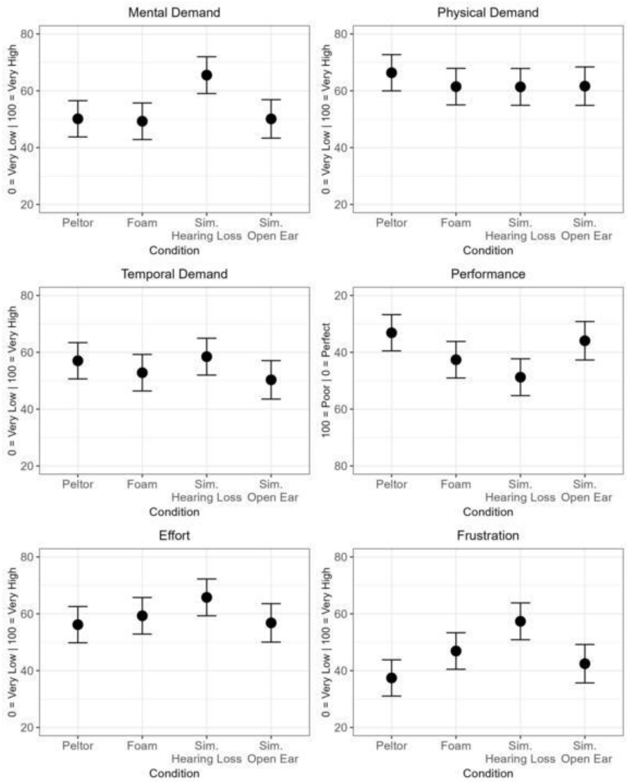


**Figure 5.** Model-fitted values for NASA Taskload Index subscales visualized as a function of hearing condition. Error bars reflect the 95% confidence interval.

Examination of the significant interaction between hearing condition and TLX subscale reveals the following: When rating levels of Mental Demand, Performance, Effort, and Frustration, participants consistently gave poorer ratings to the Simulated Hearing Loss condition as compared to all other conditions (*p*<.05, all comparisons). There were no significant differences between Simulated Hearing Loss and any of the other hearing conditions for ratings of Physical Demand or Temporal demand. Ratings of Frustration were significantly lower when using Peltors than either Foam plugs (*b*=9.48, SE=4.05, *t*=2.34, *p*=.02) or Simulated Hearing Loss (*b*=19.94, SE=4.37, *t*=270.92, *p*<.001), and were similar between Peltors and the Simulated Open Ear condition (*b*=5.02, SE=4.03, *t*=1.24, *p*=.21). The same pattern was found for ratings of Performance (Peltor vs Foam: *b*=9.48, SE=4.05, *t*=2.34, *p*=.02; Peltor vs Simulated Hearing Loss: *b*=15.63, SE=4.36, *t*=3.58, *p*<.001; Peltor vs Simulated Open Ear: *b*=2.81, SE=4.04, *t*=0.7, *p*=.49).

### 3.3 I-MILES Engagement

Preliminary analysis of the I-MILES engagement data indicates no significant effect of hearing condition. However, squads did suffer the highest number of Blue Force (BLUFOR; i.e., friendly or allied forces) casualties on average when operating with a moderate-to-severe hearing loss and the least amount when operating with the Peltors (Fig. 6). Note that all participants were resurrected in HITS by the training operators any time they were indicated as killed until the Squad conducted their final assault on the bunker to maximize the training and keep everyone in play, which is why the number of casualties often exceeds the size of the squad. Fig. 6 also illustrates that the data collected to date are highly underpowered for this analysis with only 6 observations for each condition.

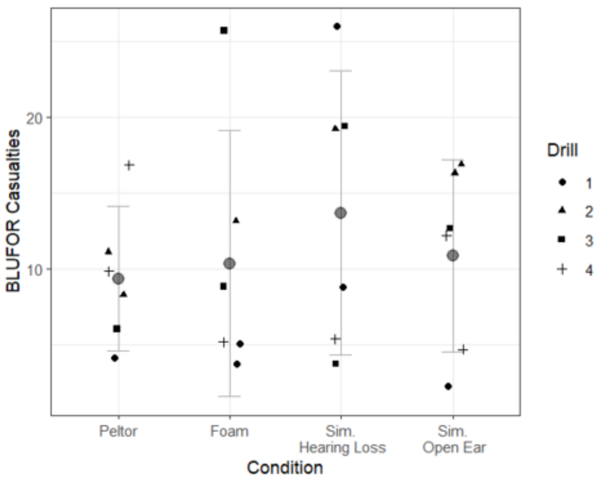


**Figure 6**. BLUFOR casualties as a function of hearing condition for each drill number. Large circles indicate mean casualties and error bars represent standard error of the mean.

### 3.4 Inertial Measurement Unit and GPS Analysis

Preliminary analysis of the IMU and GPS data is ongoing, but the early indications are that squads moved faster and spent less time in contact on average when operating with the Peltors and moved slower and spent more time in contact when operating with a moderate-to-severe hearing loss. However, these trends are not statistically significant and the data are currently underpowered for drill-level analyses.

## 4. DISCUSSION

### 4.1 Summary of Findings

The findings from this study highlight the operational advantages of advanced hearing protection devices for Soldiers in combat environments. Results indicate that Soldiers perform more effectively when equipped with these devices compared to passive foam earplugs. This underscores the critical importance of providing Soldiers with advanced hearing protection technology to enhance battlefield effectiveness.

Furthermore, the fact that the Peltor condition resulted in numerically higher OC ratings of performance than the Simulated Open Ear condition (though not statistically significant) and that Soldiers' self-ratings of performance were similar across both conditions suggests that wearing advanced hearing protection does not impose a performance cost. These findings may help alleviate concerns about potential trade-offs between hearing protection and operational effectiveness when wearing these types of advanced HPDs.

The study also demonstrates that simulated moderate-to-severe hearing loss significantly degrades performance while increasing mental demand, frustration, and effort. These factors indicate the potential for critical errors in complex operational environments if Soldiers are operating with a hearing impairment. This, too, highlights the importance of wearing effective hearing protection in combat to prevent temporary or permanent hearing loss.

Lastly, squad performance improved over time, reinforcing the effectiveness of the training exercises and underlining value of continued training and adaptation in dynamic combat scenarios.

### 4.2 Limitations and Future Directions

While these results provide valuable insights, several limitations should be acknowledged. This study represents the initial phase of data collection. Future research will expand the sample size to improve statistical power which will allow for a formal analysis of engagement data (e.g., casualties suffered). However, engagement data alone may not capture the full scope of objective performance differences, warranting a more in-depth analysis of IMU and GPS data as conducted in [6]. Furthermore, communication data analysis has yet to be conducted, and given the importance of verbal coordination in combat operations, this will be a critical area for further investigation.

A key limitation is the impracticality of blinding the OCs or participants to the hearing condition, which may have introduced bias in performance evaluations. Another limitation is the inability to test a truly open ear condition due to ethical considerations from the risk of hearing damage to the participants, which may impact some of the comparisons involving the Simulated Open Ear condition. Also, the present results evaluate only one type of advanced HPD and only one type of hearing loss. Future research will incorporate other devices and investigate some of the subtleties related to hearing impairment to provide a more comprehensive understanding of the impact of hearing acuity on Soldier performance.

## 5. CONCLUSIONS

The findings from this study can help inform Military leaders of the importance of wearing effective HPDs in combat to preserve the hearing of our Warfighters, who rely on their hearing to maintain SA and maximize operational effectiveness. The methods employed can be replicated to provide a standardized and ecologically valid assessment of other advanced HPDs and their impact on the Warfighter performance.

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## 7. REFERENCES

[1] Giguère, C., Laroche, C., Brammer, A. J., Vaillancourt, V., & Yu, G. (2011). Advanced hearing protection and communication: Progress and challenges. In *Proceedings of the 11th International Congress on Noise as a Public Health Problem* (pp. 24-28).

[2] Clasing, J. E., & Casali, J. G. (2014). Warfighter auditory situation awareness: effects of augmented hearing protection/enhancement devices and TCAPS for military ground combat applications. *International journal of audiology, 53*(sup2), S43-S52.

[3] Sheffield, B., Brungart, D., Blank, A. (2016). The Effects of Hearing Impairment on Fire Team Performance in Dismounted Combat. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 60*(1), 1509-1513.

[4] Keller, M.D., Ziriax, J.M., Barns, W., Sheffield, B., Brungart, D., Thomas, T., Jaeger, B. and Yankaskas, K. (2017). Performance in noise: Impact of reduced speech intelligibility on Sailor performance in a Navy command and control environment. *Hearing Research, 349*, 55-66.

[5] Sheffield, B., Brungart, D., Tufts, J., & Ness, J. (2017). The effects of elevated hearing thresholds on performance in a paintball simulation of individual dismounted combat. *International Journal of Audiology, 56*(sup1), 34-40.

[6] O'Donovan, M. P., Hancock, C. L., Coyne, M. E., Racicot, K., & Goodwin, G. A. (2023). Assessing the impact of dismounted infantry small unit proficiency on quantitative measures of collective military performance Part 1: Recommended test methodologies. NATICK/TR-23/013.

[7] Hancock, C. L., Teo, G. W., King, M. J., Goodwin, G. A., Pitts, K. P., Coyne, M. E., ... & O'Donovan, M. P. (2025). Quantitative team performance metrics for dismounted infantry battle drill analysis. *Applied Ergonomics*, *125*, 104473.

[8] Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology, 52*, 139-183. North-Holland.

[9] Shapiro, M. L., Norris, J. A., Wilbur, J. C., Brungart, D. S., & Clavier, O. H. (2020). TabSINT: Open-source mobile software for distributed studies of hearing. *International Journal of Audiology*, *59*(sup1), S12-S19.

[10] R Project, & Development Core Team. (2024). R Version 4.4. 1. R Project for Statistical Computing Vienna, Austria.

[11] Voeten, C. C. (2022). buildmer: Stepwise elimination and term reordering for mixed-effects regression. R package version, 2(11).