MOVING TARGETS: HOW HEARING PROTECTION SETTINGS SHIFT DISTANCE PERCEPTION

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Abstract

In noisy workplaces, wearing a hearing protection device (HPD) is mandatory but can impair situational awareness and the audibility of environmental sounds. Level-dependent HPDs amplify soft sounds to ensure audibility while still attenuating high-level sounds. However, they can also impair situational awareness, e.g., regarding localization and detection of warning signals. Distance perception is an important part of localization, e.g., in factories or at construction sites, but is rarely investigated with HPDs.

In this study, the distance of a reverse warning signal was simulated in eight steps between 1 and 25 m with virtual acoustics for playback in an 86-channel loudspeaker array. Target signals alone and with diffuse pink noise were recorded with an acoustic test fixture with open ears and wearing a level-dependent HPD in three settings. In a listening study, 32 normal-hearing participants had to identify the actual distance of the recorded signals.

The results showed impaired performance in all HPD conditions compared to open ears. Moreover, over- and underestimation of target distances varied largely between conditions, indicating risks of misperceptions when switching HPD settings during work.

Keywords: *distance perception, hearing protection, situational awareness*

1. Introduction

In noisy workplaces where daily noise exposure reaches or exceeds 85 dB(A), wearing a hearing protection device (HPD) is mandatory [1]. While HPDs reduce harmful noise exposure, they can impair the audibility of environmental sounds. Level-dependent HPDs were invented to not only provide attenuation at high levels but also facilitate communication and perception of the environment at soft to medium levels by providing hear-through modes. Such HPDs typically provide different settings with varying attenuation / amplification. However, many studies found that wearing level-dependent or passive HPDs influences situational awareness (e.g., [2], [3]). These studies mostly focus azimuthal sound source localization, sound detection and speech perception. Distance perception is rarely investigated with HPDs although it is important, e.g., when working with forklifts in factories or other vehicles on construction sites. A study by [4] found that distance estimation performance with open ears was reduced in noise, but not further with an additional HPD. However, they only tested a passive device without comparing noise conditions.

The two most important cues for distance estimation are sound pressure level and direct-to-reverberant energy ratio (DRR) [5]. Under free-field conditions, sound intensity changes over distance following the inverse-square-law [6]. The level-dependency of HPDs may alter the level cue, potentially leading to sounds that mainly differ in DRR over distance, but not in level as it would occur in open ears. Since the level-dependency varies with HPD settings, distance perception might be affected differently across settings.

To investigate these potential effects, the current study examined how an earmuff in passive and two level-dependent settings influences auditory distance perception of a tonal warning signal in a simulated factory hall, both with and without background noise. Technical measures as well as a listening study were conducted to gain insights into the relation between technical characteristics of the HPD and their influence on distance cues and perception.

2. Material and methods

2.1. Participants

In total, 32 participants (19 f, 13 m) aged 20-39 years (∅ 24.5 years) with normal hearing (pure tone av-

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erage $\leq$ 20 dB HL) took part in this study. They received an hourly compensation. All methods were approved by the ethics committee of the University of Oldenburg (protocol no. Drs.EK-2019-073-05).

2.2. Generation of distance-dependent stimuli

The target signal resembled a tonal reverse warning signal and consisted of a main frequency component at 1250 Hz, and even and odd harmonics at 2500, 3750, 5000, 6350, 7500, and 8750 Hz, which were at least 30 dB weaker than the main component. The signal had a total duration of 3 s, consisting of three 0.7 s pulses of target signal with 0.3 s pause in between.

Eight egocentric distances (1, 3, 5, 8, 11, 14, 18, 25 m) were simulated with non-linear spacing to account for increasing judgment inaccuracy beyond approx. 10 m [5]. A shoebox room resembling a large factory hall with size 50x30x10 m^3 was modelled in TASCAR [7] version 0.233.1. The room was highly reverberant with an absorption coefficient $\alpha = 0.1$ and a resulting reverberation time $T_{60} = 5.25$ s. Receiver and source were placed along the longest axis of the room and only the position of the source varied. The sound source was always placed in front of the receiver.

The signals were played back via headphones to the listeners to isolate acoustic distance cues from visual room information. The stimuli first were recorded inside an anechoic chamber with an acoustic test fixture for 2-channel playback. The anechoic chamber (size 7.5x4.0x6.0 m^3) contained an 86-channel spherical loudspeaker array with a radius of 2 m. Accordingly, the RIRs for all distances were rendered in TASCAR for 86-channel loudspeaker playback and convolved with the target signal to map the distance-dependent sound characteristics on it.

The loudspeakers type GENELEC 8030B in the anechoic room were connected to Andiamo.DA 32-channel MADI DA converters and these to an RME MADIface XT audio interface which got its signals from a PC running Matlab. An ATF type GRAS 45CA-7 equipped with a custom-made head shell [8] based on a KEMAR was placed on a platform in the middle of the loudspeaker array and used to binaurally record the distance-dependent stimuli with open ears and HPD conditions for headphone playback. The ATF's ear canals were aligned with the horizontal loudspeaker array. A GRAS 42AQ served as microphone amplifier.

The distance-dependent frontal target signals were recorded with and without diffuse pink background noise played back from all 86 loudspeakers at 70 dB SPL overall level. The level of the background noise was kept constant for all distances. In contrast, the target signal level was calibrated to 85 dB SPL at 1 m distance and decreased over distance according to the acoustic simulation down to a level of 63 dB SPL at the largest distance. Signal playback was calibrated with a sound level meter XL2 by NTi Audio, and the ATF with a GRAS 42AG multifunction sound calibrator at 1 kHz at 94 dB SPL.

A 4^{th} order 200 Hz high-pass filter was applied to the recordings without noise to suppress low-frequency interference, but not to noisy conditions to preserve noise integrity. All signals were sampled at 44100 Hz.

2.3. HPD conditions

The recordings were conducted under four HPD conditions. The first condition was open ear listening which served as a baseline. For the other three conditions, an earmuff in different settings was used.

Figure 1 shows input-output curves of the HPD conditions measured with the ATF. Circles indicate measurements with open ears. The HPD was kept in passive setting (diamonds) for the first condition, leading to a high linear damping compared to open ears. For the second and third condition, the level-dependency was switched on in medium (triangles) and maximum (squares) amplification. Medium amplification led to intermediate linear damping compared to open ears. In contrast, the incoming sound was amplified in maximum setting for levels up to 70 dB(A) and limited for higher levels.

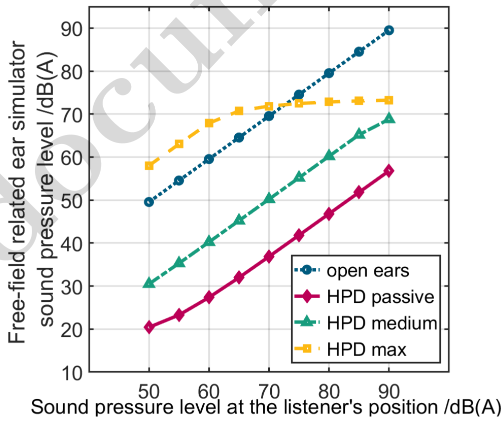

Figure 1: Free-field equalized input-output curves of the HPD for pink noise stimuli in passive mode (diamonds) and two active settings (triangles, squares), measured with the ATF. The circles represent the sound pressure level at the ear simulator microphone with open ears.

2.4. Procedure and experimental setup

The listening study took place in a sound-insulated auditory booth. Participants listened to the stimuli over Sennheiser HD 650 headphones. An equalization filter was applied to all recordings to compensate for ear canal resonance of the ATF and transfer function of the headphones, implemented as finite impulse response filter. Open-ear stimuli were used to calibrate the headphone playback to 85 dB SPL at 1 m distance. Prior to the listening tests, participants filled out the data protection form and measured a bilateral audiogram. Each participant completed eight test runs in total (4 HPD x 2 noise conditions) with 40 trials each (8 distances x 5 repetitions). The order of test runs was quasi-randomized across listeners. In each test run, the order of trials was randomized.

A display with graphical user interface (GUI, see Figure 2) in front of the listeners showed buttons for all eight distances that could be selected via mouse click. At the beginning of each run, the signals for all distances were played back once and correct distances were marked as training. During test runs, no feedback was given. A repetition of the same stimulus was not possible. The whole session took approximately one hour per participant with a break after half of the test runs.

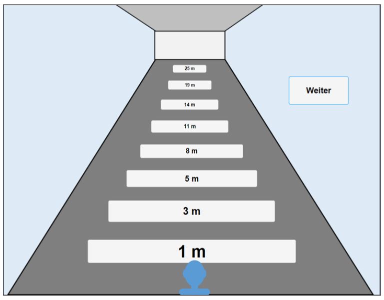

Figure 2: Matlab GUI displaying the selectable egocentric distances. The “Weiter” button (German for “next”) is used to proceed to the next stimulus.

2.5. Analysis and statistical method

The analysis consisted of three main parts. First, accuracy was assessed as percentage of correctly identified distances per condition and participant. The results were tested for statistically significant differences using a 4x2 rmANOVA for the four HPD and two noise conditions. Significant effects were followed up by pairwise t-tests with Holm-Bonferroni correction at $\alpha = 0.05$.

Second, systematic deviations between correct and estimated distance were assessed by calculating the difference between mean perceived and actual distances in steps of the GUI distances for each condition, distance and participant to reveal over- and underestimations. Additionally, the mean bias over distances per condition was calculated.

Lastly, the relationship between technical acoustic parameters and distance estimation was investigated. The root-mean-squared (RMS) level of each stimulus measured with the ATF was compared to the mean estimated distance over participants and actual distance for each HPD and noise condition. This analysis only provided insight into the overall level. Due to the non-linear processing of the HPDs, the SNR of the target signal could not be exactly extracted from the recordings. To obtain an SNR estimate, a 4^{th} order Butterworth bandpass filter with edge frequencies 1125-1375 Hz was applied to separate the target signal from the mix. Similarly, a bandstop filter in the same frequency range was used to separate the background noise. The signal-to-noise ratio (SNR) was estimated as difference between RMS-levels of filtered target and noise signals per HPD condition, and compared to mean estimated distances of participants as well.

3. Results

3.1. Estimation accuracy

Mean percentage correct estimation of distance and standard errors are depicted in Fig. 3 for all conditions. The left and right bars per HPD condition correspond to the measurements without and with noise, respectively.

Best accuracy was achieved with open ears both with and without noise. Worst distance perception was found with the passive HPD. The HPD in medium and maximum amplification led to intermediate results. Only small differences between noise conditions were observed. This was supported by the ANOVA which revealed a significant effect of HPD ($p < .001$) but not for noise condition ($p = .259$) or interactions ($p = .337$). Post-hoc t-tests of HPD condition showed that distance accuracy was significantly better with open ears than with the HPD in all settings ($p < .001$). The HPD in passive performed significantly worse than all other conditions ($p < .05$).

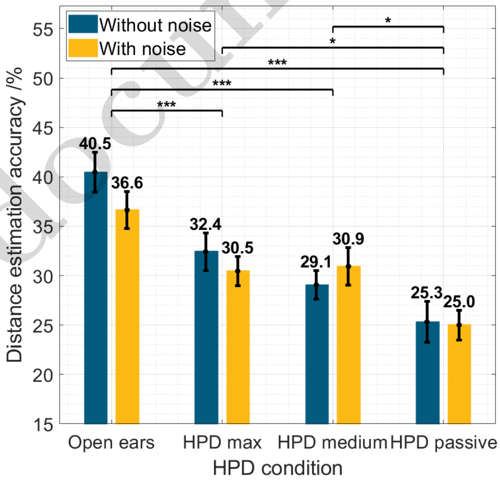

Figure 3: Mean estimation accuracy and standard errors per HPD and noise condition. Left bars per HPD condition correspond to target only condition, right bars to noisy condition. Significant differences based on 4x2 rmANOVA and Holm-Bonferroni corrected post-hoc pairwise t-tests. * $p < .05$, ** $p < .01$, *** $p < .001$. $N = 32$.

3.2. Estimation bias

Fig. 4 shows the estimation bias per presented distance and HPD condition without background noise in steps of the GUI. Horizontal lines represent the mean bias over all distances for each HPD condition. Similar linestyles correspond to the same HPD condition. A perfect distance estimation is presented as reference line at 0 steps. A bias > 0 corresponds to an overestimation (e.g., bias $= 1$ at 5 m means estimation of 8 m, i.e., 1 step above the 5-m category). Similarly, a bias < 0 represents an underestimation (e.g., bias $= -1$ means 5 m estimated as 3 m).

In all conditions, a positive bias (overestimation) was found for near distances and a negative bias (underestimation) for far distances. The crossover point is the distance where no bias occurs and where this overestimation of close distances switches to underestimation of farther distances. This crossover point is shifted between HPD conditions. With open ears, the overestimation (0.4 steps at maximum) was found until 11 m. The overall bias was slightly negative (−0.2 steps). Similarly, a negative overall bias (−0.7 steps) and the largest underestimation (−1.7 steps at 25 m) was found in maximum HPD setting. The crossover point already occurred at 3 m in this setting. In contrast, HPD medium and passive led to a positive bias for most distances. The bias at each distance (maximum 1.5 steps at 3 m) as well as the mean bias (0.6-0.7 steps) was higher than in the open-ear condition.

With background noise (not shown), similar patterns across HPD conditions were observed, but the crossover point occured as shorter distances. The HPD in passive setting led to an even higher mean (0.7 steps) and maximum (1.7 steps at 3 m) bias than without noise. The bias with HPD medium was inbetween of HPD passive and open ears at all distances.

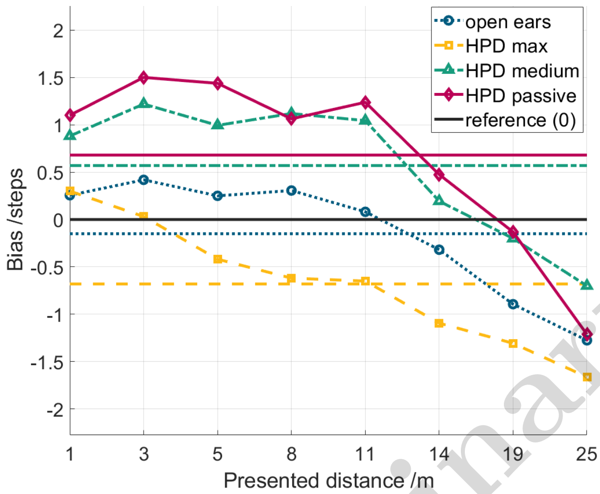

Figure 4: Estimation bias in steps of the GUI as a function of presented distance for all HPD settings without background noise. A bias > 0 corresponds to an over- and a bias < 0 to an underestimation of the presented distance. Horizontal lines represent the mean bias over all distances for the HPD condition with the same linestyle.

3.3. Relationship between technical measures and distance perception

The relationship between mean perceived distance, measured sound pressure level, and presented distance is illustrated in Fig. 5 for all HPD and noise conditions. Except for the passive HPD in the condition without noise, participants perceived the largest distance as farthest away (compare colored circles with y-axis). Moreover, the largest distances were always underestimated (as seen in Fig. 4). Nevertheless, differences in measured level are visible between all HPD and noise conditions for the same presented distances. This demonstrates how the compression behavior of different HPD settings altered the incoming sound pressure level compared to open ears.

Without noise (left panels) in open ear condition, the level decreased from 85.0 dB SPL (1 m) to 63.4 dB SPL (25 m) which corresponds to a decay of nearly 22 dB over distance. The level decreased similarly in medium and passive setting over distance but was overall attenuated. In contrast, the maximum setting led to a much smaller decay of only 6.2 dB over distance. For distances shorter than 10 m, the level in maximum setting was lower than with open ears, but higher for longer distances.

In conditions with noise (right panels), the target signal was the main contributor to overall level for near sources (up to 5 m) while the noise dominated the overall level for larger distances. The overall decay with open ears (12 dB), passive (1.3 dB) and medium (6.7 dB) HPD was smaller than without noise. In maximum setting, a slightly higher level at largest distance (77.8 dB SPL) compared to nearest distance (75.5 dB SPL) was measured. Except for this condition, higher sound pressure level always corresponded to lower perceived distances, and vice versa.

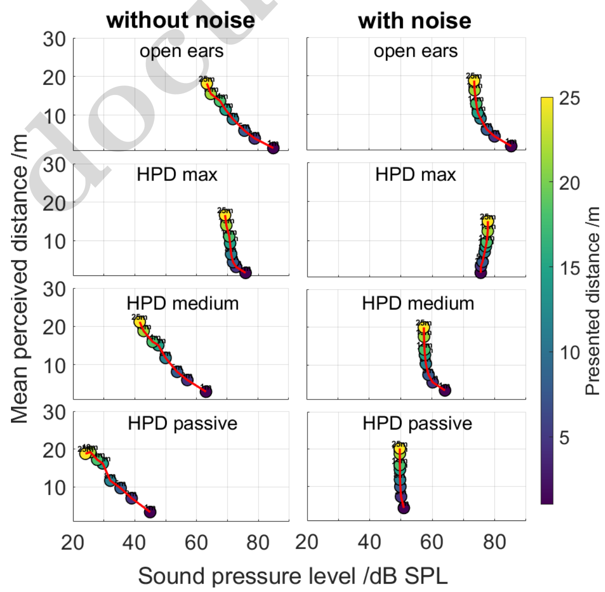

Figure 5: Mean perceived distance as function of sound pressure level at the ear simulator and presented distance for all HPDs and noise conditions.

A similar analysis was conducted regarding the mean perceived and presented distance compared to the estimated SNR in noisy conditions (see Fig, 6). In all HPD conditions, higher SNRs corresponded to shorter perceived distances. With open ears, the SNR had a similar range (20.4 dB) from shortest (16.1 dB) to longest (4.3 dB) distance as the level of target signal without noise (compare with Fig. 5). The HPD in medium and passive setting showed a similar range, although the SNR was shifted towards lower values. In contrast, the HPD in maximum setting led to a notably smaller range (11.7 dB) and a highly pronounced underestimation of target distance.

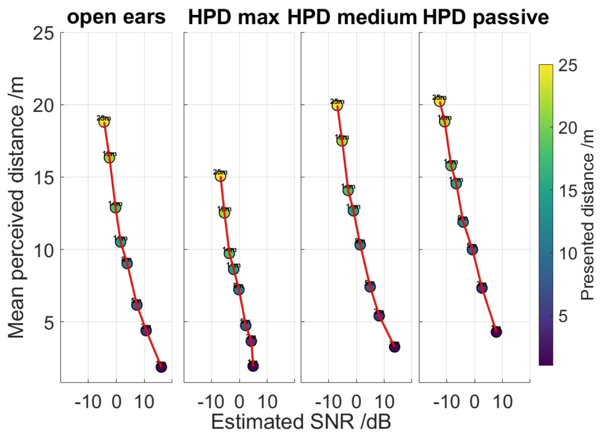

Figure 6: Relationship between mean perceived distance, SNR and presented distance for all HPD conditions in background noise.

4. Discussion

As expected, highest accuracy and smallest estimation bias were achieved with open ears. HPDs altered the level cue as well as the SNR cue and affected the distance perception. Contradictory to [4], noise did not affect distance estimation accuracy in any condition. Although [4] showed with open ears and a passive HPD that distance estimation of noise bursts worsened with open ears in noise compared to quiet, an additional passive HPD did not further reduce distance performance. However, they did not compare noise conditions with the HPD, so a direct comparison cannot be made. Nevertheless, at least differences in the open ear condition were expected. The absence of differences may relate to the tonal alarm providing a robust SNR cue, unlike the broadband noise in [4]. Although the differences in accuracy were not significant, the bias was more pronounced in noise than in quiet in all HPD conditions, suggesting that the presence of noise further reduces the reliability of distance cues and amplifies existing bias.

The bias showed over- or underestimation compared to open ear listening that is most likely connected to the attenuation or amplification in the different settings, respectively. As expected from the input-output curves, the HPD in maximum setting compressed the range of incoming level. With background noise, the incoming level was always in the limiting region, leading to similar levels across all distances. Thus, participants showed larger underestimation in maximum setting compared to open ears since an amplification of soft sounds does not resemble the natural decrease of level over distance according to the inverse-square-law. In contrast, the medium and passive setting did not compress the incoming sound, but attenuated it, leading to a higher overestimation of distance compared to open ears. This result was also found in [4]. These findings support that level is an important cue in distance perception. The higher the level of target signal, the shorter the distance, and vice versa. Additionally, passive HPDs act like a low-pass filter. Although changes in spectral cues only become relevant for distances > 15 m [5], a study by [9] showed that low-pass stimuli are consistently judged to be farther than high-pass or broadband stimuli, adding to the finding that distances with passive protection were always estimated as larger than with open ears. Under real-life conditions, such an overestimation of distance results in higher risks than an underestimation. Moreover, workers are typically unaware of the shift of the crossover point between HPD conditions, leading to a less reliable distinction between near and far sources. Over time, a consistent underestimation might lead to habituation where workers become desensitized to warning signals perceived as too close and fail to respond appropriately to actual hazards.

In the current study, this crossover point occurred around 11 m target distance with open ears. Other studies have reported the crossover point already at a distance of 1 m [4], [10]. This difference might be related to the current measurement paradigm with fixed distances (ranging from 1 to 25 m). The constraint that extreme distances could only be judged in one direction (e.g., 1 m only as correct or overestimated), combined with potential anchoring effects toward the scale's center, may have shifted the crossover point towards larger distances compared to literature data. Due to the measurement paradigm, the size of bias with HPDs might have been larger if no fixed buttons for the distances, or if no training between conditions would have been available, e.g., as in real scenarios where workers switch without training from open ears to HPD or between settings while wearing an HPD. Nevertheless, the current findings provide a first impression of how level-dependent and passive HPDs influence accuracy, estimation bias and level.

In contrast to the other conditions, the HPD in maximum setting in noise led to an inverted relation between level and distance. The HPD's temporal characteristics provide an explanation for this phenomenon. For the analysis, the RMS-value over the whole signal duration (3x0.7 s pulses in 3 s) was calculated. At far distances, the noise is the main contributor to the overall level, leading to a steady state compression over the whole signal duration. In contrast, the target signal is main contributor for close sources. Short attack times of this HPD (< 20 ms) lead to a fast adaptation towards more attenuation when the target signal is present. In the pauses between target signals, the HPD slowly releases. Since the release time (about 300 ms) is much longer than the attack time, the HPD reaches its steady state at the onset of the next target signal. This leads to a lower level at near than at far sources, providing evidence that in noisy signals, target and noise signal level should be analyzed separately.

Although the HPD in maximum setting leads to a high compression and even an inverse level-distance relation in noise, participants were still able to correctly rank distances. This suggests that participants did not rely solely on overall level but rather on other acoustic cues for distance estimation. In particular, the estimated SNR appears to provide sufficient information for distance judgments in noisy conditions. This is plausible because the HPD does not affect the target signal alone but the mixed signal. However, the SNR is based on spectral processing of the HPDs. Thus, it might be different for target and noise signals of different frequency content, between HPDs and settings. In case of target stimuli with broader frequency content than in the current study, a different method like the phase-inversion method by [11] would be necessary to extract target from noise because bandpass or bandstop filters would not be applicable.

This study comprises some limitations that should be considered. Only a static environment without head movements or moving sources was used. In reality, vehicles with warning sounds and listeners move, providing additional cues for distance perception. Moreover, only one HPD was analyzed. Thus, the current results cannot be generalized but should be diversified in future studies since temporal, spectral and amplification characteristics differ between different devices and settings. The same applies to the participants. Only normal-hearing subjects participated, but people with hearing loss work at occupational settings, too. Furthermore, stimuli were presented via headphones rather than having participants actually wear the HPDs. This may affect perception and judgments, motivating follow-up studies with participants wearing the HPDs. Lastly, although level and/or SNR seemed to act as good predictor for distance estimation, the DRR could not be analyzed because impulse responses after HPD processing were not available, potentially missing an important distance cue that could provide further insights into distance perception with HPDs.

5. Conclusion

This study investigated how level-dependent HPDs influence the auditory distance perception of a tonal warning signal with and without background noise. Best accuracy was achieved with open ears. The HPD influenced estimation accuracy and bias in all settings, suggesting altered cues that influenced distance perception. A higher damping compared to open ears resulted in an overestimation of distances on average, whereas amplification led to underestimations. Concerning all distances, near distances were overestimated and far distances underestimated. The crossover point shifted between HPD conditions, revealing a risk for workers that are unaware of this shift when switching between settings or using HPDs in general. The target signal level was found to be a main cue for the distance perception. However, further investigation of other HPDs, settings, signals, and cues such as DRR is needed to better understand how these parameters influence distance perception.

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