Editorial Commentary
Welcome to the 50th issue of the Journal
Deepak Prasher

Articles
A study on the contribution of body vibrations to the vibratory sensation induced by high-level, complex low-frequency noise
Yukio Takahashi

Preferred sound levels of portable music players and listening habits among adults: A field study
Kim R. Kähäri, T. Åslund, J. Olsson

The possible influence of noise frequency components on the health of exposed industrial workers — A review
Mahendra Prashanth Keelara Veerappa, Sridhar Venugopalchar

Evaluation by industrial workers of passive and level-dependent hearing protection devices
Jennifer B. Tufts, Mark A. Hamilton, Amanda J. Ucci, James Rubas

The sound of operation and the acoustic attenuation of the Ohmeda Medical Giraffe OmniBed™
Stephanie M. Wubben, Paul M. Brueggeman, Dennis C. Stevens, Carol C. Helseth, Kristen Blaschke

Hearing loss among classical-orchestra musicians
Esko Toppila, Heiti Koskinen, Ilmari Pykkö

Noise sensitivity and hearing disability
Marja Heinonen-Guzejev, Tapani Jauhiainen, Heikki Vuorinen, Anne Viljanen, Taina Rantanen, Markku Koskenvuo, Kaiko Heikkilä, Helena Mussalo-Rauhamaa, Jaakko Kaprio

Noise exposure of musicians of a ballet orchestra
Cheng Liang Qian, Alberto Behar, Willy Wong

Occupational exposure to noise and the prevalence of hearing loss in a Belgian military population: A cross-sectional study
Collée Audrey, Legrand Catherine, Govaerts Bernadette, Van Der Veken Paul, De Boodt Frank, Degrave Etienne

Vuvuzelas at South African soccer matches: Risks for spectators' hearing
Lebogang Ramma, Lucretia Petersen, Shajila Singh

Analysis of army-wide hearing conservation database for hearing profiles related to crew-served and individual weapon systems
William A. Ahroon, Melinda E. Hill, Dennis P. Goodes

ISSN 1463-1741
Evaluation by industrial workers of passive and level-dependent hearing protection devices

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Abstract
Level-dependent hearing protection devices (HPDs) provide protection from intense sound, while offering amplification for speech and other signals in lower levels of noise. These HPDs have been developed in response to the communication and operational needs of noise-exposed persons in industry and the military. This study was conducted to examine industrial workers’ perceptions of the performance of two level-dependent HPDs (one with integrated radio communication capability and one without it) and their customary passive HPDs. This research took place at a plastic film manufacturing plant in Rhode Island, USA, following a mixed-measures design. Fifteen maintenance technicians at the plant evaluated the two level-dependent HPDs, plus their customary passive HPDs, in three separate trial periods. Data were collected via a questionnaire designed for this purpose. Mixed-model analyses of variance were performed on all dependent measures. Linear and quadratic effect sizes were assessed with eta. Results revealed that the two level-dependent HPDs offered better perceived communication and situational awareness than the workers’ customary passive HPDs. However, the level-dependent HPDs were rated lower than the passive HPDs in terms of usability and comfort. To increase workers’ acceptance of level-dependent HPDs, usability issues must be addressed by the HPD manufacturers.

Keywords: HPD, level-dependent, sound transmission, evaluation, industry, hearing protection, noise

Introduction
A wide variety of hearing protection devices (HPDs) is available to protect the noise-exposed worker, ranging from the simple polyurethane foam earplug to the headset with integrated communication capability and noise-cancelling or amplitude-compression technology. If fitted and worn correctly and consistently, these devices provide adequate and reliable protection from hazardous noise in most circumstances.

Most HPDs worn in the workplace today are passive (such as the foam earplug), meaning that they attenuate (reduce) sound by physically blocking sound from entering the ear canal. The attenuation characteristic of a passive HPD remains the same regardless of incident sound level. This can present a disadvantage, particularly to workers in environments with fluctuating noise levels and workers who have hearing loss.

The passive attenuation that serves to protect the ear from high noise levels can reduce hearing acuity, especially during periods of relative quiet.[1] As a result, workers may wear their HPDs incorrectly (e.g., earplugs only partially inserted) or inconsistently (e.g., one earmuff lifted temporarily to hear a co-worker), if they wear HPDs at all. In response to these concerns, level-dependent HPDs have been developed by several manufacturers. Level-dependent HPDs behave like ordinary passive HPDs in high noise levels, blocking sound from entering the ear canal. However, in lower noise levels or in quiet, they are acoustically transparent, i.e. ambient sounds are delivered to the ear unaltered or with slight amplification. Transparent hearing is typically provided via separate microphones for each ear, preserving localization cues. A disadvantage of level-dependent HPDs, from an employer’s point of view, could be their significantly greater up-front cost relative to passive HPDs. (The claim by some manufacturers that the life-cycle cost of a level-dependent HPD is lower than the cost of passive HPDs over an equivalent time period is not evaluated here.) The provision of level-dependent HPDs to some or all employees may also represent a cultural change for a company. From this perspective, studies of workers’ perceptions of the field performance of level-dependent HPDs are valuable. First, they can document the real-world benefits and disadvantages of wearing level-dependent HPDs from the workers’ point of view. Second, they can assess workers’ acceptance (or non-acceptance) of the technology.
Tufts, et al.: Evaluation of level-dependent HPDs

Third, they can provide practical feedback to developers of level-dependent HPDs in order to improve performance and increase end-user acceptability.

The purpose of the current study was to evaluate noise-exposed workers’ perceptions of the field performance of two level-dependent HPDs. The two HPDs were similar in all respects except that one had integrated radio communication capability and one did not. We hypothesized that relative to the workers’ customary, passive HPDs, the level-dependent HPDs would provide better perceived communication capability and situational awareness and thus be preferred to the passive HPDs. We also hypothesized that the HPD with integrated radio communication capability would be preferred over the others by workers who use radios to communicate at work. All study procedures were approved by the Institutional Review Board of the University of Connecticut.

Methods

Participants

Fifteen employees of a plastic film manufacturing plant in Rhode Island, USA, were recruited for participation in the study (mean age = 39.5 years; SD = 6.3). All participants were male, and all were enrolled in the company’s hearing conservation program (meaning that their 8-h time-weighted-average (TWA) noise exposures were 85 dBA or greater), as stipulated by the U.S. Occupational Safety and Health Administration. Although many more employees were enrolled in the company’s hearing conservation program, the logistics of shift scheduling precluded their participation. The participants in this study typically worked 8 a.m. to 5 p.m. shifts Monday through Friday. All were maintenance technicians, responsible for maintenance and upkeep of the process machinery and the facilities, and all communicated face-to-face and via radio. All had had air-conduction thresholds tested within the last year as part of the hearing conservation program [Table 1]. Personal noise dosimetry was conducted by a private testing firm during the same period that data collection for this study took place. Three of the study participants were monitored for a single day; their 8-h TWAs on that day were 84, 85 and 93 dBA.

Each participant signed an informed consent form prior to participation in the study. Following the consent procedure, each participant filled out a questionnaire about his workplace noise exposure, hearing ability, and HPD use. Table 2 lists questionnaire responses for each subject. As shown in Table 2, eight subjects had normal or essentially normal hearing. Two had bilateral mild-to-moderate hearing losses. The remaining five subjects had losses that fell in-between these two extremes. In general, self-reported hearing ability grossly matched audiometric status. Fourteen subjects experienced tinnitus either never or less than 10% of the time. The remaining subject, one of the two with a bilateral mild-to-moderate hearing loss, experienced tinnitus 50-75% of the time. On average, the subjects had spent 8.2 years in their current jobs (range: 3-18 years). They reported spending an average of 26.7 h per week in noise on the job (range: 10-40 h). Self-reported HPD use was high, with 2 subjects reporting HPD use 75-90% of the time when in noise at work and the remaining 13 reporting HPD use more than 90% of the time. (It should be noted that the company maintained a strict disciplinary policy with regard to HPD use in high-noise areas.)

The subjects were asked to rate the importance of being able

Table 1: Audiometric thresholds of the study participants (in dB HL), measured within the year prior to data collection as part of the company hearing conservation program

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Noise & Health, January-February 2011, Volume 13
to hear various workplace sounds. The following sounds (not in rank order) were rated as “very important” to be able to hear by at least 12 of the 15 subjects: voices of other person(s) close by, radio communications, machinery or tools (both when operating correctly and when in need of repair), moving vehicles, and alerting/warning signals. Subjects were asked how easy it was to hear these sounds while wearing and while not wearing their customary HPDs. Answers to these questions varied. However, two trends emerged: alerting/warning signals were judged as being easier to hear than speech and machinery sounds, and all sounds were easier to hear without passive HPDs than with passive HPDs.

**Level-dependent HPDs—general description**

Two level-dependent HPDs were evaluated in this study. The first device, Phonak Serenity DP (for dynamic protection; hereafter referred to as DP), consisted of a processor and an AAA battery housed in a plastic casing (approximately 7.5 cm × 4 cm × 1.5 cm). The unit had a clip for securing it to clothing, a lanyard for wearing it around the neck, and two detachable cords running to two small plastic earpieces, one for each ear. Each earpiece held an omni-directional electret condenser microphone on one side for picking up ambient sound and a miniature loudspeaker on the other side for delivering the processed sound into the user’s ear canal. The two channels were processed independently to allow binaural hearing. The earpieces were designed with a tab and flanges that allowed them to snap into specially constructed custom earmolds (described in a later section) worn by the user. An on-off switch was integrated into the unit’s battery.
Before the start of data collection, the electroacoustic device was fabricated at the Phonak facility in Murten, Switzerland. Earmolds were worn by the user. Binaural earmold impressions of each participant were taken at the workplace by a licensed audiologist. Earmolds were hypoallergenic medical-grade nylon and were highly durable. Because the same earmolds could be worn with either the DP or DPC, they were made of lightweight and hypoallergenic medical-grade nylon and were highly durable. Earmolds were worn by the user. The earmolds were hollow, with the faceplate designed to accommodate the earpieces as passive HPDs. When the unit was off, the earpieces/earmolds acted as passive HPDs. When the unit was switched on, ambient sound was picked up by the microphones on each earpiece and amplified by the processor. Two buttons on the side of the unit allowed the user to control the amplified sound level. Starting from the default level, the level could be increased by 6 dB or decreased by 15 dB, with a step size of 3 dB. The buttons controlled the output level of both channels. With the volume control at the default setting, the output level of the device was nearly equal to the input level, that is, the device was set to unity gain. This default level was chosen by the manufacturer to provide “transparency” of sound for the user. Ambient sound above approximately 78 dB SPL was compression-limited. According to the manufacturer, maximum output (measured at 2000 Hz with input ≥78 dB SPL and the volume control at the highest setting) was maintained at 84 dBA free-field equivalent. Protection against impulse sounds was provided by the digital signal processor, which did not transmit impulses to the miniature loudspeaker.

The second device, Phonak Serenity primero DPC (for dynamic protection and communication; hereafter DPC), was physically and operationally similar to the DP, except that radio communication capability was integrated into the device. Connected to the bottom of the processor unit was a radio interface cable at the free end for attachment to a Motorola HT1000 radio (for this specific application). To send radio communications, the user depressed either the radio’s push-to-talk (PTT) button or the PTT button located on the front of the processor unit. The user’s voice was picked up via an in-ear microphone located on one of the earpieces, processed through a speech-extraction algorithm using blind-source-separation technology, and transmitted over the radio. Incoming radio communications were relayed diotically to the in-ear receivers at a level of 92 dBA free-field equivalent or lower, depending on the radio volume setting. Figure 1 shows the DPC. The DPC looked identical to the DP except that it did not have a radio interface cable at the bottom of the processor unit.

As mentioned previously, the earpieces of the DP and DPC were designed to snap into specially designed custom earmolds worn by the user. The earmolds were hollow, with the faceplate designed to accommodate the earpieces of either the DP or DPC. They were made of lightweight and hypoallergenic medical-grade nylon and were highly durable. Earmolds were fabricated at the Phonak facility in Murten, Switzerland.

Prior to the start of data collection, the electroacoustic function of each device was tested in an Audioscan Verifit electroacoustic test box. The radio function of each DPC device was tested in a Frye Electronics Fonix 6500-CX electroacoustic test box. All devices appeared to be functioning appropriately and similarly. A biological listening check on each device also indicated proper function.

**Evaluation questionnaire**

A questionnaire was developed to measure participants’ subjective impressions of the HPDs under evaluation. The format and content of the questionnaire were loosely adapted from the “Beliefs about Hearing Protection and Hearing Loss” survey (including the use of a 5-point rating scale), but individual questionnaire items were added or modified for the specific application in this study. The questionnaire was vetted by several lay persons for clarity before being distributed to study participants. The first questions established compliance with protocol (e.g. “Did you wear any other hearing protector over the last two weeks, besides the one circled above?”). Next, a series of statements relating to various aspects of HPD performance were presented. These statements were adapted, in large part, from the “Beliefs about Hearing Protection and Hearing Loss” survey, the “Satisfaction with Amplification in Daily Life (SADL)” scale, and Phonak’s in-house questionnaires. The statements included items relating to speech and radio communication in noise and in quiet, physical and auditory comfort, perceived sound quality, and situational awareness. An additional set of statements was presented on the ease/difficulty of operating the level-dependent HPDs. These statements were adapted largely from “Measure of Audiologic Rehabilitation Self-Efficacy for Hearing Aids (MARS-HA)”. Positive and negative versions of each statement were created. For example, the positive version of one statement read “My hearing protectors are comfortable,” while the negative version read “My hearing protectors...”
are uncomfortable.” Two forms of the questionnaire were developed. Each form contained an equal number of positive and negative statements. The positive statements on one form were presented as the negative versions on the other form, and vice versa. For example, the positive statement “My hearing protectors are comfortable” was given on the first form, while the corresponding negative statement “My hearing protectors are uncomfortable” was given on the second form. The statements were presented in a different, randomized order on each form. Participants rated how often they agreed with each statement using the categories “almost always,” “often,” “about half of the time,” “sometimes,” and “rarely.”

At the end of the questionnaire, participants were asked to rate how satisfied they were with the assigned HPD on a five-point scale ranging from “very satisfied” to “very dissatisfied.” Responses were coded such that a high score indicated greater satisfaction with the device and a low score indicated lesser satisfaction. Finally, they were asked two open-ended questions, “What do you like about this hearing protector?” and “What do you dislike about this hearing protector?” Total time to complete the questionnaire was approximately 5 min.

**Procedures**

Participants evaluated the two level-dependent HPDs (DP and DPC) in two separate trial periods. They evaluated their regularly worn passive HPDs (hereafter passive) in another trial period. To eliminate HPD testing order effects, participants were divided into three groups of five each. The division into groups was made primarily on the basis of air-conduction thresholds. An effort was made to distribute hearing levels as evenly as possible across all three groups, so that each group had members with normal hearing, with mild hearing loss, and with mild-moderate hearing loss in at least one ear. The order in which the HPDs were tested was assigned to the groups according to a modified Latin Square design. Group A evaluated the HPDs in the order Passive--DP--DPC; Group B evaluated the HPDs in the order DP--DPC--Passive; and Group C tested the HPDs in the order DPC--Passive--DP. Thus, at any given time, one group was wearing their regular passive HPDs, another group was wearing DP devices, and the third group was wearing DPC devices.

At the start of each trial period, participants were trained individually on their assigned HPDs and instructed to wear only those HPDs for the entire trial period. Training took place near the start of the day’s work shift, in a small conference room at the plant. Those who were assigned to wear the level-dependent HPDs received about 5 to 10 min of training on the wearing and operation of their devices. They were also instructed on earmold insertion and removal. Those who were assigned to their regular HPDs were asked to wear their HPDs in the customary way during the trial period. Devices and earmolds that were not being used were collected by the investigators to discourage use of devices other than the ones assigned.

Each trial lasted 10 consecutive working days. At the end of each trial period (usually a Friday), the plant safety manager distributed the evaluation questionnaires to the participants. The two forms of the questionnaire were distributed such that at the ends of the trial periods, six people (three from Group A, one from Group B, and two from Group C) received Form 1, then Form 2, then Form 1, while eight people (two from Group A and three each from Groups B and C) received Form 2, then Form 1, then Form 2. One subject from Group B received three versions of Form 1 due to investigator error. The questionnaires were collected by the investigators at the plant, usually the following Monday. Following the three trial periods, after all questionnaires had been completed, each participant filled out an “exit survey” in which he rank-ordered the HPDs (Passive, DP, and DPC) in answer to the question, “If you could wear only one type of hearing protector at work day after day, which would you choose?” Responses were coded such that a high score indicated greater preference for the device and a low score indicated lesser preference. In subsequent analysis, this ranking is referred to as “overall preference.”

Thirteen of the 15 subjects followed the experimental schedule as described above. One subject started 2 weeks later than the others, and another began 4 weeks later. Both completed all three trial periods. On occasion, an employee missed from 1 to 5 days of a 10-day trial period due to illness or vacation. However, every employee completed at least 5 days with each device, and most completed the full 10 days.

Prior to the start of the trial periods, the amount of passive attenuation obtained by each user with his earmolds was measured with Phonak’s proprietary in-situ fit-testing system. All participants obtained adequate attenuation, defined as attenuation meeting or exceeding the values specified in EN 352-2 “Hearing protectors—General requirements—Part 2: Ear-plugs.”[5] Attenuation measurements were reported as individual single number ratings (SNRs) and individual high-frequency (H’), medium-frequency (M’), and low-frequency (L’) attenuation values, analogous to the SNR, H, M, and L values defined in ISO 4869 “Acoustics—Hearing protectors - Part 1: Subjective method for the measurement of sound attenuation”.[6] The average SNR for all subjects was 27.6 dB (range: 21-33 dB). Average H’, M’, and L’ values were 28.9 dB (range: 24-32 dB), 24.1 dB (range: 17-30 dB), and 21.4 dB (range: 13-26 dB), respectively.

**Dependent measures**

The questionnaire items were assessed for content validity and internal consistency. The analysis was based on 45 judgments per item (15 subjects × three HPD types); for those items specifically related to operation of the level-dependent HPDs, the analysis was based on 30 judgments per item (15 subjects × two HPD types). Before the correlations
among the items were analyzed, responses to the items were recoded so that a higher value always indicated agreement with the positively-worded version of the item (and a lower value indicated disagreement). Analysis of the part-whole (item-scale) correlations and item content indicated that two general perceptions, auditory functionality and comfort, were present in the items related to various aspects of HPD performance. Two specific perceptions, ease of device startup and ease of sound adjustment, were present in the items related to operation of the level-dependent HPDs. Table 3 lists the questionnaire items comprising each of these four dependent measures.

Answers to the open-ended questions “What do you like/dislike about this hearing protector?” were coded into categories according to content and weighted as either +1 or -1 depending on valence (positive or negative). The categories are listed in Table 4 under two emergent themes, convenience/usability and ability to communicate while wearing a device. The weightings given to the responses falling within each category are listed next to the category name. Weighted responses were summed across participants to compute scores for the two themes. Table 4 also lists the questionnaire items used to measure satisfaction and overall preference.

Results

For the purpose of analysis, the eight dependent variables described in the previous section were grouped into two pairs of perception measures [Table 3] and two pairs of assessment measures [Table 4]. The first pair of perception measures included the specific perceptions (ease of device startup and ease of sound adjustment); the second pair of perception measures included the general perceptions (auditory functionality and comfort). The first pair of assessment measures included the themes emerging from the responses of the participants to the questions “What do you like/dislike about this hearing protector?” (convenience/usability and ability to communicate while wearing the device). The second pair of assessment measures included satisfaction and overall preference.

Preliminary analyses for each pair of variables consisted of two tests. First, the extent to which order of exposure to HPD type moderated the effect of HPD type on each dependent variable was assessed. For the four perception variables, questionnaire form was also considered as a moderator of HPD effects. This mixed-model analysis of variance (ANOVA) consisted of form (two levels) and order (three levels) as between-subjects factors and HPD type (three levels) as a within-subjects factor. (For the four assessment measures, form was not relevant.) Second, Mauchley’s W was used to test for violations of the assumption of sphericity. On all eight dependent measures, the $\chi^2$ test on the W-value obtained was not significant.

In the main analysis, a reduced model, consisting only of the within-subjects factor of HPD type, was tested. Because they did not produce systematic effects on the dependent variables,
the between-subjects factors of form and order were removed from the model, thereby increasing the available degrees of freedom. For each dependent variable, means and standard deviations for each HPD type, and the linear and quadratic effects of HPD type were calculated. The means and standard deviations are listed in Table 5. By assigning the levels of HPD type in the order Passive, DP, DPC, the linear effect of HPD type represented the addition of progressively more technology, whereas the quadratic effect of HPD type isolated the impact of the DP.

Perception measures

First, the DP and DPC devices were compared on ease of device startup and ease of sound adjustment. Preliminary analysis indicated that no between-subjects effects of form or order were present for either dependent measure (all Fs ns). For ease of device startup, the analysis did show a form by HPD-type interaction: F(1, 9) = 19.89, P = 0.002 and a small main effect for HPD type: F(1, 9) = 6.53, P = 0.03. For ease of sound adjustment, the analysis revealed a form by order by HPD-type interaction: F(2, 9) = 4.74, P = 0.04, but no main effect for HPD type: F(1, 9) = 1.36, P = 0.27. Examination of the means showed no coherent trends. The nominal interactions were likely due to sampling error, so they were ignored in subsequent analysis.

In the reduced model, the main effect of HPD type was not present for either ease of device startup: F(1, 14) = 2.24, P = 0.16 or ease of sound adjustment: F(1, 14) = 0.32, P = 0.58. The means of both ease of device startup and ease of sound adjustment were approximately the same for the DP and DPC. These findings suggest that the study participants found the DP and DPC devices to be very—and equally—easy to operate [Figure 2 and Table 5].

With auditory functionality as the dependent measure, the preliminary analysis indicated that no between-subjects effects were present (all Fs ns). The analysis did show a form by order by HPD-type interaction. Form and order appeared to interact with HPD type to produce a quadratic effect: F(2, 9) = 15.69, P = 0.01, but not a linear effect: F(2, 9) = 1.28, P = 0.33. This interaction was due to one of the six (form by order) means in the DP condition deviating from the main effects expected values. The nominal nature of the interaction suggested that it was likely due to sampling error, so it was ignored in subsequent analysis. There was a substantial main effect for HPD type: F(2, 18) = 16.08, P < 0.001.

In the reduced model for auditory functionality, the impact of HPD type was separated into linear and quadratic effects. The linear effect was moderately large: F(1, 14) = 7.31, P = 0.02, eta = 0.42, as was the quadratic effect: F(1, 14) = 9.11, P = 0.01, eta = 0.44. The means indicated that the DP performed most favorably, followed by DPC, with the passive HPDs performing least favorably [Figure 3 and Table 5].

With comfort as the dependent measure, the means indicated that the passive HPDs were rated most favorably, followed by DPC. These findings suggest that the study participants found the DP and DPC devices to be very—and equally—comfortable to wear [Table 5].

<table>
<thead>
<tr>
<th>HPD Type</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>4.51</td>
<td>0.69</td>
</tr>
<tr>
<td>DP</td>
<td>4.80</td>
<td>0.46</td>
</tr>
<tr>
<td>DPC</td>
<td>4.90</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 4: Under general assessments, questionnaire items used to assess satisfaction and overall preference are listed. Under specific assessments, two themes are listed, convenience/usability and ability to communicate while wearing the device.

<table>
<thead>
<tr>
<th>General assessments</th>
<th>Specific assessments</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Satisfaction</td>
<td>I. Convenience/usability</td>
</tr>
<tr>
<td></td>
<td>Weighting</td>
</tr>
<tr>
<td>II. Overall preference</td>
<td>1. Easy to use</td>
</tr>
<tr>
<td></td>
<td>2. No hassles</td>
</tr>
<tr>
<td></td>
<td>3. Difficulty with physical aspects of device (e.g., wires)</td>
</tr>
<tr>
<td></td>
<td>4. Difficulty with radio operation (e.g., interruption of face-to-face communication by radio)</td>
</tr>
<tr>
<td></td>
<td>II. Ability to communicate while wearing the device</td>
</tr>
<tr>
<td></td>
<td>1. Improved face-to-face communication with device on</td>
</tr>
<tr>
<td></td>
<td>2. Improved radio communication with device on</td>
</tr>
<tr>
<td></td>
<td>3. Difficulty hearing with device on</td>
</tr>
</tbody>
</table>

The themes of convenience/usability and ability to communicate while wearing the device emerged from the coding of answers to the open-ended questions “What do you like/dislike about this hearing protector?” Specific coded categories are listed under each theme. The weighting given to each response falling within a category is listed next to the category name.

Table 5: Means and standard deviations for the passive, DP, and DPC HPDs for all eight dependent measures

<table>
<thead>
<tr>
<th>HPD Type</th>
<th>Passive</th>
<th></th>
<th>DP</th>
<th></th>
<th>DPC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Ease of device startup</td>
<td>n/a</td>
<td>n/a</td>
<td>4.51</td>
<td>0.69</td>
<td>4.30</td>
<td>0.67</td>
</tr>
<tr>
<td>Ease of sound adjustment</td>
<td>n/a</td>
<td>n/a</td>
<td>4.80</td>
<td>0.46</td>
<td>4.90</td>
<td>0.39</td>
</tr>
<tr>
<td>Auditory functionality</td>
<td>3.10</td>
<td>0.51</td>
<td>3.87</td>
<td>0.81</td>
<td>3.64</td>
<td>0.71</td>
</tr>
<tr>
<td>Comfort</td>
<td>4.63</td>
<td>0.48</td>
<td>4.23</td>
<td>1.06</td>
<td>4.12</td>
<td>0.64</td>
</tr>
<tr>
<td>Convenience/usability</td>
<td>0.60</td>
<td>0.63</td>
<td>-0.33</td>
<td>0.72</td>
<td>-0.80</td>
<td>0.41</td>
</tr>
<tr>
<td>Ability to communicate</td>
<td>-0.27</td>
<td>0.46</td>
<td>0.53</td>
<td>0.52</td>
<td>0.47</td>
<td>0.52</td>
</tr>
<tr>
<td>Satisfaction</td>
<td>3.73</td>
<td>1.08</td>
<td>4.07</td>
<td>0.80</td>
<td>3.20</td>
<td>0.96</td>
</tr>
<tr>
<td>Overall preference</td>
<td>1.87</td>
<td>0.74</td>
<td>2.67</td>
<td>0.62</td>
<td>1.36</td>
<td>0.50</td>
</tr>
</tbody>
</table>

(DP = Phonak Serenity DP; DPC = Phonak Primero DPC; n/a = not applicable)
by DP, with DPC rated least favorably [Figure 3 and Table 5]. The preliminary analysis indicated that no between-subjects effects were present, nor did HPD type interact with either form or order (all Fs ns). The effect of HPD type was not significant: $F(2, 18) = 2.13, P = 0.13$, yet the effect size was moderate: $\eta = 0.36$. Given the promising effect size, a reduced model for comfort was tested. A medium-sized but non-significant linear effect was present: $F(1, 14) = 2.82, P = 0.12, \eta = 0.34$. The quadratic effect was small: $F(1, 14) = 0.87, P = 0.37, \eta = 0.04$ [See Endnote].

**Assessment measures**

With convenience/usability as the dependent measure, the preliminary analysis indicated that no between-subjects effects were present, nor did HPD type interact with order (all Fs ns). There was a significant main effect for HPD type: $F(2, 18) = 16.15, P < 0.001$. In the reduced model, the impact of HPD type was separated into linear and quadratic effects. The negative linear effect was extremely large: $F(1, 14) = 35.48, P < 0.001, \eta = 0.85$. The quadratic effect was of moderate size: $F(1, 14) = 1.36, \text{ns, } \eta = 0.29$. The means indicated that the passive HPDs were most convenient to use, followed by DP, with DPC least convenient to use [Figure 4 and Table 5].

For ability to communicate while wearing the device, no between-subjects effects were present, nor did HPD type interact with order (all Fs ns). There was a significant main effect for HPD type: $F(2, 18) = 10.17, P < 0.001$. In the reduced model, the positive linear effect was very large: $F(1, 14) = 12.64, P < 0.001, \eta = 0.69$, as was the quadratic effect: $F(1, 14) = 8.89, P = 0.01, \eta = 0.62$. The means indicated that DP facilitated communication the most, followed by DPC, with the passive HPDs least facilitative [Figure 4 and Table 5].

With satisfaction as the dependent measure, the preliminary analysis indicated no main effect for order: $F(2, 12) =$

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Figure 2: Means and standard deviations for ease of device startup and ease of sound adjustment for the DP and DPC HPDs (5 = best, 1 = worst; passive not evaluated). (DP = Phonak Serenity DP; DPC = Phonak Primero DPC.)

Figure 3: Means and standard deviations for auditory functionality and comfort for the passive, DP and DPC HPDs (5 = best, 1 = worst). (DP = Phonak Serenity DP; DPC = Phonak Primero DPC.)
2.27, \( P = 0.15 \), nor did order interact with HPD type: \( F(4, 24) = 1.73, P = 0.18 \). The main effect for HPD type was significant: \( F(2, 18) = 3.56, P = 0.05 \). In the reduced model, the negative linear effect was of moderate size: \( F(1, 14) = 2.52, P = 0.13, \text{eta} = 0.29 \). The positive quadratic effect was somewhat larger: \( F(1, 14) = 6.00, P = 0.03, \text{eta} = 0.37 \). Participants were most satisfied with DP, followed by the passive HPDs, and least satisfied with DPC [Figure 5 and Table 5].

For overall preference, the preliminary analysis indicated no main effect for order: \( F(2, 12) = 0.00, P = 1.00 \), nor did order interact with HPD type: \( F(4, 20) = 0.27, P = 0.90 \). The main effect for HPD type was significant: \( F(2, 22) = 10.02, P < 0.001 \). In the reduced model, a moderate-sized but non-significant linear effect was observed: \( F(1, 14) = 2.97, P = 0.11, \text{eta} = 0.27 \). The quadratic effect, however, was very large: \( F(1, 14) = 15.68, P < 0.001, \text{eta} = 0.60 \). DP was most preferred, followed by the passive HPDs, with DPC least preferred [Figure 5 and Table 5].

**Discussion**

Noise-exposed workers at a manufacturing plant in Rhode Island evaluated the performance of two level-dependent HPDs (DP and DPC) and their customary passive HPDs. DPC had integrated radio communication capability, whereas DP did not; otherwise, the two level-dependent HPDs were physically and operationally similar. We hypothesized that DP and DPC would be preferred over the passive HPDs because they would provide better perceived communication capability and situational awareness. We also hypothesized that DPC would be preferred over DP and Passive by workers who use radios to communicate.
Following trial periods with all three HPDs, workers ranked-ordered them in response to the question, “If you could wear only one type of hearing protector at work day after day, which would you choose?” From most to least preferred, they ranked the HPDs in the order DP-Passive-DPC. After each trial period, workers were asked how satisfied they were with the assigned HPD. Mean ratings of satisfaction followed the same rank order, DP-Passive-DPC. The assessments of satisfaction and preference represented a kind of “bottom-line” evaluation of the attributes of the HPDs, because they required the study participants to integrate information across multiple dimensions to arrive at their answers. Our initial study hypotheses suggested a rank ordering of DPC-DP-Passive. To understand why the rank ordering of DP-Passive-DPC emerged, we looked to the other dependent measures.

Recall that for ability to communicate while wearing the device, mean ratings, from best to worst, fell in the order DP-DPC-Passive; for convenience/usability, the order was Passive-DP-DPC. That is, the level-dependent HPDs were better at facilitating communication, but were less convenient and presented more obstacles to use than the passive HPDs. These observations were corroborated by the results for the scales of auditory functionality and comfort. Auditory functionality encompassed various aspects of HPD use specifically related to hearing, including communication and situational awareness [Table 3]. On this measure, the level-dependent HPDs performed better than the passive HPDs. On the other hand, there was a trend toward decreased comfort for the level-dependent HPDs relative to the passive HPDs. In summary, the level-dependent HPDs offered improved communication and situational awareness compared with the passive HPDs. Indeed, comments made by the study participants about hearing with the level-dependent HPDs tended to be positive (e.g.: “I can hear people talking much more clearly”; “Hear much better—like a hearing aid”), whereas comments about hearing with passive HPDs tended to be more negative (e.g., “It’s hard to hear some equipment sounds and conversations with foam plugs”). However, the improvements in hearing with the level-dependent HPDs contrasted with the increased inconvenience and greater number of usability issues that were encountered (e.g.: “Bulky, when working, sometimes gets in the way”; “Wires getting caught while working”) in comparison with the passive HPDs (e.g.: “I like that they are disposable and didn’t have to worry about damaging them”; “Easy to use. No wires to get in the way”).

Comparing the two level-dependent HPDs directly, DP offered better communication and fewer usability obstacles than DPC. Not surprisingly, DP also outperformed DPC on the auditory functionality and comfort scales. Upon review of the study participants’ comments about the two level-dependent HPDs, it appeared that practical issues related to radio communication were the source of dissatisfaction with DPC (e.g., “You cannot hear the person you are talking to when there is someone on the radio”; “Earpieces need to be in to be able to use the radio”).

The study participants’ rank-orderings of overall preference in the order DP-Passive-DPC appeared to capture a perceived tradeoff between the benefits and drawbacks of level-dependent HPD technology in their workplace. DP was most highly preferred likely because it offered better communication and auditory functionality than the passive HPDs, and fewer practical obstacles than DPC. However, the lower preference for DPC may have been related not only to practical obstacles, but also to characteristics of the particular workplace environment in this study. The advantages of in-ear microphone and integrated communication technology would tend to become most apparent under extremely adverse communication conditions, conditions much worse than those typically encountered by the participants in this study. All other things being equal, satisfaction with DPC might have increased if the workplace environment had been more hostile to communication. Even in the current environment, comments about the quality of radio communication with DPC tended to be positive (e.g., “Improved radio communication in loud areas”).

Level-dependent HPDs offer promising benefits for the protection of the hearing-impaired worker. Workers with hearing loss can be difficult to protect appropriately because of the risk of overprotection. By amplifying speech and other sounds during periods of relative quiet, level-dependent HPDs can restore the hearing that is lost due to wearing the HPD, and may even partially overcome the pre-existing hearing loss. Nine of the 15 participants in this study had normal or near-normal hearing and two had mild bilateral losses. Future studies with hearing-impaired workers are essential.

In this study, some of the benefits and drawbacks of level-dependent versus passive HPDs from the workers’ point of view were measurable even with a small convenience sample of 15. Studies utilizing larger N’s, hearing-impaired workers, a variety of environmental conditions/job types, and objective as well as subjective measures will continue to move the development of level-dependent HPD technology forward. Indeed, since this research was conducted, new developments have occurred in both of the level-dependent HPDs evaluated in this study.

**Endnote**

Although neither the linear nor the quadratic effect of comfort was statistically significant, the moderate linear effect size suggested that aspects of comfort were worth exploring with a covariance analysis. The correlation between auditory functionality and comfort averaged across the three HPD types was positive ($r = 0.32$). Recall that the addition of progressively more HPD technology had a positive linear effect on auditory functionality but a negative effect on comfort. The positive correlation between auditory functionality and comfort indicates that the effect of HPD type on one of the two dependent
variables in the ANOVA was suppressed. Given that the effect of HPD type on auditory functionality was moderately large on average and the effect on comfort moderately small, it appeared that suppression was occurring on comfort. This meant that the effect of HPD type on comfort should be larger once auditory functionality was controlled for in an ANCOVA. The negative linear effect of HPD type on the covariate-adjusted comfort variable was indeed large: $F(1,14) = 15.99, P < 0.001$, eta = 0.52. The quadratic effect of HPD type on the covariate-adjusted comfort variable was moderately large: $F(1,14) = 6.79, P = 0.02$, eta = 0.40. The covariance analysis increased the linear effect of HPD type on comfort from moderate to large and the quadratic effect from small to moderately large. Thus, the amount of suppression on comfort was substantial. This result suggests opposing effects on comfort such that the addition of technology decreased comfort, whereas auditory functionality increased comfort.

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References