The Effects of Simulated Hearing Loss on Speech Recognition and Walking Navigation

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Objective: The objective was to assess whether a concurrent but independent navigation task exacerbates the effects of hearing loss on speech recognition and whether hearing loss degrades performance of the navigation task during the concurrent but independent listening task.

Background: Navigation performance and speech comprehension both decrease when a driver follows hard-to-hear concurrent verbal instructions. It remains unknown how much both tasks would be affected when performed concurrently, if tasks were independent.

Method: Participants performed a listening task by responding to Callsign Acquisition Test (CAT) stimuli at three simulated hearing levels. For each hearing level, one trial was performed with the participant standing still and another trial was performed while navigating a path in a virtual environment using a handheld map. In one more trial, participants navigated a path with no CAT. The proportion of call signs correctly repeated and the total time required to walk the path were measured.

Results: CAT scores showed an expected negative effect of hearing loss. Concurrent navigation produced an even larger decrease in CAT score. Hearing loss caused a slight but not significant decrease in navigation task performance.

Conclusion: A person with hearing loss may communicate less effectively while walking than predicted on the basis of hearing loss alone. The hearing loss, however, does not significantly decrease walking performance in a simple navigation task.

Application: Obtained results may guide soldier performance modeling and requirements for communication systems used during physical activity when a soldier’s hearing becomes compromised during dismounted combat operations.

Keywords: speech, hearing, walking, navigation, hearing loss, executive attention, task interference, dual independent tasks

INTRODUCTION

Loud impulsive and continuous noises produced by weapons and military vehicles cause significant hearing loss among many U.S. soldiers and marines. Hearing loss is a widespread, severe, and costly problem to many military veterans returning from service (National Research Council, 2006). Although hearing conservation programs exist and hearing protection devices are available, these measures have limited effectiveness (Saunders & Griest, 2009). Most importantly, hearing loss degrades the soldier’s ability to understand direct commands and radio messages, making it more difficult for the soldier to operate as a member of a squad and increasing the soldier’s vulnerability. In addition, reduced hearing ability creates situation awareness problems for soldiers operating on the battlefield.

Effects of Hearing Loss on Military Communication

The impacts of reduced intelligibility and difficulty of hearing have been demonstrated in simulation studies involving combat vehicle and aircraft environments. As intercrew communication intelligibility decreased, combat performance metrics degraded: The time to identify enemy targets increased, the number of enemy targets destroyed decreased, the number of friendly targets destroyed increased, and the number of (simulated) casualties among vehicle crews increased (Garinther & Peters, 1990; Garinther, Whitaker, & Peters, 1994; Peters & Garinther, 1990; Whitaker, 1991; Whitaker, Peters, & Garinther, 1989, 1990). In the case of the aircraft environment, flight characteristics, such as speed and altitude, became more varied, and deviations from the prescribed flight path increased with combinations of increased workload, poor communications signal quality, and decreased speech intelligibility (Casto & Casali, 2010; Valimont, Casali, & Lancaster, 2006). In general, as intelligibility of the task-related
communications decreased, the task performance also decreased in an almost linear manner (Garinther & Peters, 1990). However, to fully evaluate the impact of hearing loss on human performance, one must consider possible effects of hearing loss on the tasks concurrent to speech communication that do not rely on hearing and do not necessarily require auditory information.

**Attentional Cost of Multitasking**

Dividing attention between multiple tasks involving various modalities produces varied effects on task performance, depending on the number of tasks; their difficulty, interrelation, and relative priorities; and experience and capabilities of the person performing these tasks (cf. Wickens, 2002; Wickens, Goh, Helleberg, Horrey, & Talleur, 2003). The complex demands of multitasking are most commonly examined in research involving dual-task performance (Damos, 1991). The two concurrent tasks can be discrete, continuous, or combinations of both. One of the tasks can be the primary task, or both tasks can be equally important. When both of the tasks are performed concurrently, the performance on each of the tasks usually decreases in comparison to the single-task performance (Horrey & Wickens, 2003; Wickens, 1991).

As reported by several authors, attention and training are important factors in ensuring completion of several concurrent time-critical tasks that require divided attention (Bherer et al., 2005; Strayer, Drews, & Johnston, 2003; Strayer & Johnston, 2001). Hafter, Bonnel, Gallun, and Cohen (1998) suggested that the primary determinant of cost in dual-task activities is the processing mode used by the performer. They also argued that the reference to sensory traces does not affect dual-task performance, whereas reference to absolute standards does. In addition, the decrease in dual-task performance has been reported to be a function of aging and degree of similarity between the tasks involved (e.g., Hartley & Little, 1999; Holtzer, Stern, & Rakitin, 2005; McDowd & Shaw, 2000; Navon & Miller, 1987; Verhaeghen & Cerella, 2002).

The mechanisms involved in performance decline resulting from dual-task activities have been conceptually described by multiple resource theory (Wickens, 1991). However, although dual-task activities have been studied extensively, it is still unclear whether dual-task performance is limited by certain centrally shared attentional resources, a single-channel capacity level that operates on one of the tasks at a time (the bottleneck theory), or processing cross talk (Pashler & Johnston, 1998). It is clear, though, that decrements in dual-task performance depend on many uncertain psychological, cognitive, and physical factors as well as detailed aspects of the specific tasks (Wickens et al., 2003). Therefore, regardless of the actual mechanisms affecting dual-task performance, empirical experimental evaluation remains invaluable in quantifying performance in dual-task scenarios.

Military activities are seldom single-task duties and usually involve two or more tasks performed concurrently. Activities often involve concurrent performance of several time-critical tasks involving both mental and physical activities. An example of such situations is attending to radio traffic while conducting other tasks frequently unrelated to the radio traffic, such as walking, running, and visually searching for battlefield threats. When hearing is degraded, additional attention may be required to understand verbal signals and auditory cues.

Increased attention requirements may interfere with motor tasks, even if the motor tasks do not depend on received auditory information. Strayer and Johnston (2001) assessed the effects of cellular phone conversations on simultaneous driving performance and reported a twofold increase in failures to detect traffic signals and substantial delays in reaction to the signals that were presented and detected. Beauchet and Berrut (2006) observed decreased performance in dual-task activity involving response to verbal messages and walking. Similarly, Hatfield and Murphy (2007) and Nasar, Hecht, and Wener (2008) reported that the use of a mobile phone caused a decrease in situation awareness and an increase in pedestrian behavior judged unsafe. Certain people with compromised neurological capabilities stop walking when they enter into a conversation (Beauchet et al., 2009; Hyndman & Ashburn, 2004; Lundin-Olsson,
Nyberg, & Gustafson, 1997), indicating that attention required by verbal and auditory processes can decrease walking performance. A dual-task study involving healthy young adults demonstrated that executive attention requirements increase during performance of increasingly more complex gait tasks (Siu, Catena, Chou, Donkelaar, & Woolacott, 2008). Thus, reported research findings indicate that the impact of hearing loss may extend well beyond the normal reduction in communication ability.

### Effects of Hearing Loss on Independent Tasks

In studies by Garinther and Peters (1990) and Whitaker (1991), successful task performance depended on information in the compromised speech messages. The metric tasks performed were not independent of the speech and hearing processes; task performance had to degrade with poorer communication. Similar inference can be made regarding the data obtained by Whitaker, McCloskey, and Peters (2003) using a dual-task instruction-driven game-playing task.

Many studies have demonstrated the impact of decreased communication on vehicle operations, but few similar studies address the impact of hearing difficulty on independent physical task performance of soldiers operating on foot (dismounted). Although hearing loss is a significant problem among dismounted infantry veterans (National Research Council, 2006), the precise mechanisms and the full impact of hearing loss on dismounted operations remains uncertain. Results from cited mounted studies offer only limited insight because dismounted operations involve significantly different workloads—physiological and cognitive—and different communication and hearing requirements, as well as different threats and threat-induced stresses, than do mounted operations. The full impact of hearing loss on dismounted soldier performance remains unclear and cannot be accurately determined on the basis of studies of vehicle operation and the studies in which speech communication is inherently related to the main operational task.

### Purpose of the Study

The goal of this study was to determine to what degree hearing loss influences the performance of independent listening and navigation tasks when they are performed together. It was hypothesized that the adverse impact of hearing loss will be greater during the simultaneous performance of listening and navigating tasks and that the impact may decrease the navigation task performance even though the navigation task requires no input from the listening task.

### METHOD

#### Participants

A group of 16 army civilian employees between 20 and 45 years old participated in the study. Of the participants, 9 were male and 7 were female. Although the tasks performed in this study were relevant to tasks soldiers perform during military operations, military training or experience was not required to successfully execute the performed tasks. Participants were required to be in good physical condition and able to walk for up to 2.8 miles on the Human Research and Engineering Directorate’s Omni-Directional Treadmill (ODT), described later.

All participants had normal bilateral hearing defined as 25 dB HL (hearing level in reference to standard audiometric threshold) or better hearing thresholds measured with pure-tone air conduction audiometry at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. Normal outer-ear status and middle-ear function were confirmed by otoscopy and ear impedance testing, respectively. We assessed normality of vestibular function by asking the participants about any cases of chronic vertigo (none) and observing participant behavior during the ODT walking training session. During ODT training sessions, 2 potential participants incurred light vertigo and were disqualified from the study. Informed consent was obtained from each qualified participant prior to his or her participation in the research study. All data were collected in compliance with regulations from the Institutional Review Board at the U.S. Army Research Laboratory.

#### Instrumentation

### Test stimuli. The Callsign Acquisition Test (CAT; Rao & Letowski, 2006) for testing recognition of militarily relevant speech material was
used to measure the speech recognition ability of the participants in all test conditions. The CAT contains 126 call signs. A single item consists of a word and a number. The word is a two-syllable military alphabet code, and the number is a one-syllable number (e.g., alpha 1 or bravo 2). The CAT items were presented at the most comfortable listening level for listening in noise (see section on ODT). The use of most comfortable level rather than a fixed dB SPL allowed for some compensation of small differences in hearing thresholds among the participants. The CAT phrases were played via Sound Forge software on a Dell personal computer through a Shure Wireless Personal Monitor System. The participants heard the phrases through a pair of Coby Sound Isolation Digital Stereo Earphones. A Sennheiser Evolution wireless microphone system was used to record the participants’ repetition of the CAT stimuli.

Military functional capabilities for hearing criteria are profiled as H1 to H4. Condition H1 corresponds to normal or better hearing; conditions H2, H3, and H4 correspond to mild, moderate, and severe hearing impairment, respectively. The specific hearing threshold levels for each hearing profile are specified in Army Regulation 40-501 (Department of the Army, 2008, p. 80). To simulate auditory abilities of people with normal hearing (profile H1) and with two different levels of hearing impairment (profiles H2 and H3), we presented a normal version and two modified versions of the CAT to participants. H4 was not used. To simulate H2 and H3 hearing profiles, we used two audiometric pure-tone hearing-threshold configurations representative of H2 and H3 types of hearing. We simulated hearing loss representative of the H2 hearing profile by decreasing signal spectrum levels by 15 dB at 500 Hz, 30 dB at 1000 Hz and 2000 Hz, 45 dB at 3000 Hz and 4000 Hz, and 55 dB at 6000 Hz. We simulated hearing loss representative of the H3 hearing profile by decreasing signal spectrum levels by 20 dB at 500 Hz, 35 dB at 1000 Hz and 2000 Hz, 55 dB at 3000 Hz and 4000 Hz, and 65 dB at 6000 Hz. Both simulated profiles were bilaterally symmetrical. Spectral equalizations as mentioned previously are commonly used in audiology to simulate hearing loss for patient education, research, and development of hearing aids (Desloge, Reed, Braids, Perez, & Delhorne, 2010; Rawool, 2012).

All volunteers participating in the study had normal hearing with individual differences within normal hearing criteria. Obviously, such differences alter to some degree the audibility of the test signals. Therefore, to compensate for some of these individual differences, the volunteers were asked to adjust their earphone signal level at the H1 listening condition to match their self-assessed most comfortable listening level and to use this earphone setting at all other hearing level conditions.

The ODT. Walking navigation was conducted with an ODT located in the Immersive Environment Simulator (IES). The IES is a simulator for the dismounted soldier that combines the ODT with visually immersive virtual environments, enabling natural locomotion through the environments. The IES integrates a RAVE II display, the ODT, and a camera-based motion tracking system. The RAVE II is a reconfigurable video display system consisting of four 3.81 m × 3.05 m (12.5 ft × 10 ft) rear-projected modules. It is used to display a 360° field of view of the virtual terrain that the user is traversing. The ODT has a 2.44 m × 2.44 m (8 ft × 8 ft) working surface that allows the user to walk in any direction without leaving the working surface. The maximum speed of the ODT is limited to 1.79 m/s (4 mph). Figure 1 shows a person walking on the ODT in the IES.
A validation study was conducted to compare walking on the ODT with walking over ground for selected biomechanical and physiological variables and to quantify any significant differences (Boynton, Kehring, & White, 2011). Motion capture, gait analysis, and cardiopulmonary measurement techniques were employed to obtain objective measures of temporal-spatial gait parameters, sagittal plane joint kinematics, and metabolic cost for 10 participants walking at two speeds (1.12 m/s and 1.34 m/s) along a circular course (4.3-m radius) over ground and in the IES along an identical circular course in the simulated environment. The results of the study showed that users walk on the ODT with gait mechanics and joint kinematics similar to those used over ground but expend more energy doing so. The increased metabolic cost may be attributable to the adoption of a different muscle coordination strategy on the ODT to achieve a natural gait pattern. This difference between over-ground and ODT walking needs to be taken into consideration when comparing the results of studies involving prolonged walking whereby physical fatigue may be an issue; however, it will have little effect when walking for short intervals and at a self-selected pace (which tends to be the most energy efficient).

The noise level produced by the ODT depends on the speed of walking and varies slightly as a function of walker direction. Therefore, an additional masking noise of 85 dB A-weighted (measured in the center of the treadmill) was used in the study. Background noise was a pink noise, which has similar spectral properties to city traffic noise and was therefore selected for the study. The noise was produced by a set of four QSC HPR 122i Powered Sound Reinforcement Loudspeakers: one speaker located behind the screens below the ODT surface on each of the four sides. The spectrum of the combined ODT and pink noise is shown in Figure 2.

Walking environment. The participants walked on the ODT in a virtual environment along designated routes. The route to be walked was given to the participant on a map of the simulated environment. There were four routes, each approximately 1,000 m in length, used in the study. The time needed to walk along each route was approximately 11 min. A route similar to those used in the study is shown in Figure 3.

To maintain approximately the same level of difficulty of each route, we included two walking paths on the map. Both paths were similar in length: Path 1 was 942 m and Path 2 was 933 m. Each path could be walked in both directions, creating four distinct routes. All routes had similar level of difficulty (number and distribution of turns). The assignment of routes to test conditions (no CAT, H1, H2, and H3) was

![Figure 2. Spectrum of the combined Omni-Directional Treadmill and pink noise.](image)
counterbalanced, and each participant walked each route once. Such arrangement allowed a participant to walk along a different route in each test condition.

Procedure

The participants received test instruction and training on how to walk and navigate on the ODT before they participated in the study. Participants practiced walking freely in all directions on the ODT until they felt comfortable doing so and appeared to have no hesitation or issues with their balance. Before participating in the walking and navigation tasks of the study, participants were given a map and were asked to walk and navigate a training path that was similar to, but shorter than, the study paths. ODT training was complete after participants successfully navigated the training path. Participants were also familiarized with the CAT phrases by listening and responding to CAT stimuli in quiet while standing on the ODT. The goal of the CAT familiarization session was to ensure that all participants could hear and properly pronounce all CAT items correctly when listening to them in quiet. Participants were instructed to repeat the call sign immediately after each call sign was presented. When participants were adequately trained in navigating the path, listening to and repeating call signs, and doing both tasks concurrently, the experimental trials began.

At the beginning of each test trial, the experimenters provided the participants with a map of the path that they were required to traverse. Each path had designated starting and end points. The experimenters oriented the walker at the starting point facing the path direction, prior to the start of each trial. Participants were instructed to move at a fast but safe pace, that is, to walk as fast as possible without running, to reach the end of the path.

As the participants walked, they listened for CAT phrases played through earphones and repeated them aloud. The goal of this task was to assess the participant’s ability to recognize speech items in specific test conditions. Listening to radio communications and acknowledging transmitted call signs while moving is a typical soldier task during patrolling, search-and-rescue missions, and other similar military operations. If the call sign heard in radio traffic matches the call sign assigned to the specific soldier or unit, the soldier responds by repeating the call sign,

![Figure 3. An example of a route used during the study. Route starts at point S, passes waypoint W, and ends at point E.](image)
indicating that he or she is in communication (Department of the Army, 2009).

Each participant wore a wireless microphone system (described previously), and all CAT responses were recorded for further analysis. If the participant made a wrong turn and continued walking, he or she was immediately verbally redirected by the experimenters to ensure that the participant walked along the designated path. Participants were told that correctly repeating the CAT call signs and completing the walking task as well and as quickly as possible were both equally important tasks.

The walking task was performed once with no CAT test (control condition) and once with a simultaneous CAT test presented at each level of simulated hearing loss, for a total of four walking trials per test participant, or a total of 64 walking trials. In addition, at each level of simulated hearing loss, the CAT task was performed once while the test participant was standing stationary on the ODT. In sum, the study consisted of 7 trials per test participant for a total of 112 trials, 16 of which had no CAT. Total background masking noise at 85 dB A-weighted was presented during all trials.

**Experimental Design**

The design of this study was within subjects with two independent variables: CAT presentation with four levels (none, H1, H2, H3) and walking task difficulty with two levels (walking, not walking). The dependent variables in this study were measures of speech recognition and walking performance. The speech recognition metric used was the percentage correct of the repeated CAT items. Walking performance was determined by the completion time for each path and the average walking speed of the participant. In addition to the completion time, the walking performance was evaluated by counting the number of times that a participant was redirected to the designated path after making a wrong turn. CAT scoring was suspended during redirection. Scoring was restarted when the participant returned to the specified route. The number of test participants was determined by counterbalancing the four CAT presentation conditions with four paths, which required 16 test participants. In addition, three nonwalking trials (conditions H1, H2, and H3) were randomized and interlaced between the walking trials.

**RESULTS AND DATA ANALYSIS**

To test uniformity of the data set across test participants, we labeled the participants in three binary ways according to the potential secondary variables that could affect the data. The labels were participant’s gender (male or female), experience with the ODT (yes or no), and experience with the CAT (yes or no). Cluster analysis was performed on all individual CAT scores and navigation task completion time data. The cluster analysis did not show any participant’s grouping related to the three binary variables, so the data were combined across all participants in subsequent analyses.

Average CAT scores obtained in the study presented as a function of the type of simulated hearing loss are shown in Figure 4. The data shown in this graph as well as throughout the whole paper are presented as the percentage of correct scores. However, many of the CAT scores occurred near the highest value in the score range, 1.0, which corresponds to all responses being correct. Such data do not have properties of normal distributions and need to be normalized for the purpose of statistical analysis of the data. Therefore, to reduce non-normality in CAT score data, the data were non-linearly transformed to rationalized arcsine units (rau; Studebaker, 1985). The arcsine transform stretches the domain of proportional values near the maximum and minimum, increasing the normal characteristics of domain-limited distributions. The rationalized arcsine transform adjusts the overall domain to more closely preserve the values of proportions between 0.15 and 0.85 while symmetrizing the enhancement of normality at the upper and lower limits of the proportional domain.

A 2 (walking) × 3 (hearing loss) within-subjects ANOVA with CAT scores in rau units as the dependent variable showed a significant decrease in CAT scores as the level of simulated hearing loss increased, \( F(1.896, 28.444) = 129.1, p < .001 \). CAT scores were nonhomogeneous, and a Greenhouse-Geisser correction of 0.948 was applied, producing fractional degrees of freedom.
The concurrent walking task also decreased overall CAT scores, \( F(1, 15) = 83.6, p < .001 \). A comparison between CAT scores with and without concurrent navigation task is shown in Figure 5. A significant interaction between hearing loss and walking or not walking was observed, \( F(1.59, 23.84) = 15.07, p < .001 \). Tukey HSD post hoc tests showed that CAT scores at the H1 level (no hearing loss) were significantly different from CAT scores at the H2 and H3 hearing loss levels \( (p < .001) \). No significant differences were found between walking and not-walking CAT scores with no hearing loss, between H2 and H3 CAT scores while not walking, and between H2 and H3 CAT scores while walking \( (p = .085) \). In Figure 5, CAT scores identified by different letter labels were significantly different.

Figure 6 shows average navigation task completion times for all conditions of speech comprehension difficulty used in this study (no CAT, H1, H2, H3). Although the navigation task decreased CAT scores with the increased levels of simulated hearing loss, CAT task performance and simulated hearing loss had no significant influence on the completion time of the simple navigation task used in this study, \( F(1, 15) = 2.62, p = .127 \).

**DISCUSSION**

Average CAT performance showed a significantly greater decrease as a function of simulated hearing loss level for the walking condition as compared with the nonwalking condition. In the normal hearing condition (H1), CAT performance showed no significant decrease associated with the navigation task, indicating that otologically normal adults have sufficient resources to perform the speech recognition task when speech is easily heard while performing the walking navigation task. However, speech recognition (CAT score) significantly decreased...
with increased hearing loss, especially with the additional navigation task. Figure 4 illustrates the speech recognition decline as a function of simulated hearing loss; Figure 5 shows that performing the parallel navigation task produces a larger decrement in speech recognition score than does the hearing loss alone.

The navigation task completion time showed no significant effect from concurrent performance of the speech communication task, either with or
without simulated hearing loss. The navigation task employed in this study was relatively easy. Although the speech communication task and the navigation task both represent realistic tasks performed when a soldier moves on foot and listens to and communicates over the radio, navigation task performance did not show a significant decrease when performed with the parallel speech communication task regardless of hearing loss. On the basis of the data obtained for these simple tasks, however, we cannot rule out that more demanding tasks may show significant effects bidirectionally.

It is also possible that the effect of a real hearing loss on the navigation task may be greater than that observed for the simulated hearing loss, which was simulated with only a frequency-dependent amplitude reduction and reflected no accompanying decrease in temporal sound resolution. The limitations of the filtering-based simulated hearing have been discussed in the literature (Desloge et al., 2010; Moore, 2007; Rawool, 2012). However, because of problems with simultaneous simulation of all the aspects of hearing loss, simulations limited to signal filtering are common first approximations of hearing loss in simulation studies addressing human auditory performance and not-hearing physiology modeling. Thus, the reported data seem to lead to two observations: (a) that even with constrained filter-based simulation of hearing loss, the effects of hearing loss are exacerbated by walking and (b) that hearing loss simulated by signal filtering may be insufficient to observe some more subtle effects of real hearing loss on human performance.

The overall relationship between the navigation task completion time and CAT score is shown in Figure 7. This relationship shows a lack of clear differences in participants’ CAT data in H2 and H3 simulated conditions. Whereas similar observations can be inferred from Figures 5 and 6, the data distribution presented in Figure 7
CONCLUSIONS

Within the constraints of our study, the navigation task had a significant adverse influence on the speech recognition task performance when a simulated hearing loss was applied. This finding indicates that hearing loss causes an increase in resources needed to perform speech communication and walking tasks simultaneously. This influence may be important not only in the case of a permanent threshold shift but even for a temporary threshold shift, which a soldier may experience on the battlefield. This finding implies that if a soldier were to experience hearing loss, his or her speech recognition ability could decrease further if the soldier was moving.

Although multiple resource theory could predict reduced walking performance given a demand for attention caused by listening difficulty from hearing loss (Horrey & Wickens, 2003), multiple resource theory does not require an effect, and we observed no significant effect of simulated hearing loss on navigation task performance. This finding may be a result of the relatively easy navigation task (Horrey & Wickens, 2003). Another explanation for this finding may be that the overall workload increased, the listening task was given less effort, allowing performance of the navigation task to remain unperturbed. We conclude that in the context of our specific militarily relevant tasks, the effects of speech recognition difficulties on independent walking task performance remain of little concern.

Further research in this area should address a more concentration-intensive physical task performed with speech communication by participants with actual hearing impairment.

Simulated hearing loss accounts for a decrease in hearing sensitivity, but it does not account for poorer spectral and temporal resolution typically associated with the hearing loss.

KEY POINTS

- Listening task performance by a listener with a simulated hearing loss was affected more severely when the listener was walking as compared to the stationary condition.
- Simple navigation task performed by a listener with a simulated hearing loss was not significantly affected by a concurrent speech recognition task. However, the observed trend may indicate possible decrease in performance during more complex navigation tasks.

REFERENCES


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