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An evaluation of digital cellular handsets by hearing aid users

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Abstract—Audible interference from digital cellular telephones (cell phones) has been a long standing problem for hearing aid users. The Federal Communications Commission (FCC) has lifted the hearing aid compatibility exception on cell phones and imposed a set of requirements effective September 2005. We conducted an experiment to determine how well hearing aid wearers are able to use commercially available digital cell phones. Hearing aid users evaluated the usability of six digital cellular handsets. The results suggest that certain transmission technologies create more annoyance from interference than others and that the type of hearing aid-to-telephone coupling (microphone or telecoil) can influence a user's experience of interference. However, the results also suggest that interference alone does not fully predict the usability of a cell phone for hearing aid users. These findings have implications for the American National Standards Institute C63.19 test and measurement standard that is used to rate cell phones' compliance with the FCC ruling and the education of consumers with regard to their expectations for cell phone use.

Key words: cellular handset, digital cell phone, hearing aid, hearing aid compatibility, interference, microphone coupling, telecoil coupling, transmission technology, usability, wireless telephone.

INTRODUCTION

Cellular telephones (cell phones) have become one of the most important consumer communication technologies worldwide. The Cellular Telecommunications and Internet Association estimates that as of December 2004, more than 180 million people in the United States alone subscribe to cell phone service [1]. As the technology has spread, interest in the usability of these phones by people who have hearing loss has grown. Unfortunately, today's cell phone technologies can be incompatible with hearing aids and cause audible interference when the hearing aid wearer uses a cell phone. This article traces the technological developments, industry activity, consumer activism, and government policies that have led to a change in the hearing aid compatibility requirements for digital cell phones. We then report the results of a field study in which hearing aid wearers evaluated digital cellular handsets across a range of listening variables.

Over the last 9 years, the cell phone industry in the United States has transitioned from analog to digital

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Abbreviations: ANSI = American National Standards Institute, BTE = behind the ear, CDMA = code division multiple access, FCC = Federal Communications Commission, GSM = Global System for Mobile Communications, HAC = hearing aid compatibility, HIA = Hearing Industry Association, iDEN = Integrated Digital Enhanced Network, RERC = Rehabilitation Engineering Research Center, RF = radio frequency, SHHH = Self-Help for Hard of Hearing People.

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technology. The benefits of digital technology are many: smaller handsets, longer battery life, a wide array of features and settings customizable to the user, and multimedia services (e.g., data, radio, television). Digital technology also provides the capability to support increased calling traffic on networks and to store information in the handset and on carriers' servers. This technology and its benefits have not been fully accessible to many hearing aid users because of the properties of digital signal transmission.

Before digital cell phone technology was introduced in the United States, data from Europe and Australia demonstrated that normal use of a digital cell phone with a hearing aid frequently results in an annoying buzzing sound that interferes with speech intelligibility and limits the usability of the phone. The underlying source of the interference is the digital cellular signal transmission. When communicating with cellular network base stations, the handsets use various patterns of rapid on-off transmission to multiplex the signal; hearing aids pick up the electromagnetic energy and demodulate the transmission patterns as buzzing, clicking, popping, or other noise. (Analog transmission did not cause such interference.)

It is important to note that some digital cell phones are quite usable by some hearing aid wearers. However, the interaction between cell phones and hearing aids is complex and involves factors related to both devices, and prediction of individual performance has been nearly impossible. Hearing aids that are worn in the ear canal and have small components and low exposure to the cell phone emissions are generally less susceptible to cell phone interference than larger hearing aids worn behind the ear [2]. Over the last several years, many hearing aid manufacturers have increased their use of components that are less susceptible to cell phone radio frequency (RF) emissions. Tests on a large number of hearing aids from the major hearing aid manufacturers have shown that over the 6-year period from 1997 to 2003, the immunity of hearing aids to RF emissions has increased by more that 30 dB for microphone coupling [3]. However, hearing aids in telecoil coupling mode are likely more susceptible to interference from cell phones than hearing aids in microphone coupling mode because telecoils are also susceptible to the audio-band interference from magnetic emissions that are produced by handset electronics. Certain cell phone transmission technologies, particularly Global System for Mobile Communications (GSM) (widely used by two national cell phone service providers), have been shown in laboratory studies to cause interference that is more annoying and more disruptive to speech intelligibility than other technologies [2]. Handset design may also influence interference levels. In particular, designs such as "flip-style phones" may reduce interference levels because they provide greater distance between the hearing aid and the cell phone components that cause interference [4]. The complexity of these device-related factors and the lack of specific product information for both hearing aids and cell phones have led to considerable consumer confusion and frustration. The only reliable advice to hearing aid wearers from the industry has been "try before you buy," which has been an impractical solution for many people because of the complexities of cell phone service contracts and limitations in the number of "live phones" available for test calls in retail outlets.

Since 1995, the consumer organization Self-Help for Hard of Hearing People, Inc. (SHHH), has implored the cell phone industry, the hearing aid industry, and the Federal Communications Commission (FCC) to solve the interference problem. The FCC, when petitioned on the issue, encouraged voluntary efforts and initially declined to impose requirements on the cell phone industry. Research by companies and universities was performed, and the two industries collaborated on the development of a standard for predicting user experience based on independent performance measures of cell phones and hearing aids [5]. However, the resulting American National Standards Institute (ANSI) C63.19 standard was not subsequently implemented by the industries. The hearing aid industry, responding to concerns from governments of other countries, improved immunity to cell phone interference in some hearing aids. Unfortunately, no progress was made in publicly identifying which cell phones might be usable with reasonably immune hearing aids. Despite the work of the late 1990s, hearing aid wearers had no solution.

After conducting a formal proceeding on digital cell phones and hearing aids in 2003, the FCC issued a rule that requires handset manufacturers and service providers to make available a limited number of handsets that meet the FCC's requirements for hearing aid compatibility [6]. The Commission cited the Hearing Aid Compatibility Act of 1988, which requires all corded and cordless landline telephones sold in the United States be capable of wireless coupling to hearing aids. The law had provisionally exempted cell phones but directed the Commission to periodically review the exemption and lift it, if warranted according to defined criteria. These criteria include the impact on hearing aid wearers, public interest, and technical feasibility. In partially lifting this exemption, the FCC granted a phase-in period of 3 years. The first requirement took effect in the fall of 2005 [7]. The FCC requirement is designed to ensure that, at all times, some cell phones that work well with reasonably immune hearing aids will be available from almost every carrier and manufacturer (with some exemptions for small companies). Hearing aid compatibility (HAC) in landline phones refers primarily to telecoil compatibility, and landline phones must meet FCC requirements for audio-band magnetic fields. Because interference impedes usability, the FCC defines HAC for cell phones in terms of handset emissions as well as telecoil coupling. The rule relies on the ANSI C63.19 standard for the HAC specification. The standard addressed two types of electromagnetic emissions: RF emissions, which are implicated in hearing aid interference with both microphone and telecoil coupling; and magnetic emissions, which contribute to hearing aid interference with telecoil coupling. In addition, the standard addressed the performance of the handset in providing the intended speech signal through magnetic coupling to the telecoil.

An important component of the FCC rule is that handset manufacturers and cell phone service providers must clearly identify handsets that meet or exceed the requirements by labeling the cell phone packaging and by providing an explanation of the FCC requirement in the product insert. (The handsets themselves do not have to be labeled.) **Table 1** shows the timeline for implementation of the FCC rule.

Although the FCC does not have jurisdiction over hearing aids, the agency encouraged the hearing aid industry to test its products for immunity and disclose which hearing aids would work well with digital cell phones. For their part, the Hearing Industry Association (HIA) (the trade organization for hearing aid manufacturers) has committed to identifying hearing aids that have higher immunity levels and would be compatible with cell phones that meet the FCC requirement. This does not mean, however,

Table 1.
Federal Communications Commission (FCC) timeline for hearing aid compatibility in cell phones.

Date	Number of Handsets	Requirement	Benefit
September 2005	2 handset models per handset manufacturer and carrier for each transmission technology. For largest carriers, 4 handset models or 25% of total number of handset models offered.	Must meet FCC requirement for reduced RF emissions. M3 and M4 are compliant ratings, with M4 being better rating. (Acoustic output is not evaluated as part of this rating, and there is no volume control requirement.)	Primarily benefits hearing aid wearers who use M mode for cell phone listening. Compliant handsets will be compatible with hearing aids that have a reasonable amount of immunity but not necessarily with every hearing aid.
September 2006	For largest carriers, 5 handset models or 25% of total number of handset models offered.	Must meet FCC requirement for reduced RF emissions at M3 or better.	Increases requirement for largest carriers, which benefits hearing aid wearers who use M mode for cell phone listening.
	2 handset models per handset manufacturer and carrier for each transmission technology.	Must meet FCC requirement for T coupling, which includes specified levels of intended magnetic field strength, specified frequency response, and reduced audio-band magnetic emissions. T3 and T4 are compliant ratings, with T4 being better rating.	Benefits hearing aid wearers who use T mode for cell phone listening. Compliant handsets will be compatible with hearing aids that have a reasonable amount of immunity, but not necessarily with every hearing aid.
February 2008	At least 50% of all handset models for each transmission technology.	Must meet FCC requirement for reduced RF emissions at M3 or better.	Makes available large selection of handsets that can be used with a variety of hearing aids in M mode.

M = microphone, RF = radio frequency, T = telecoil.

that hearing aids will be labeled according to their immunity level. The HIA is reluctant to agree to a labeling system because they believe the highly customized nature of hearing aids and unique characteristics of individual hearing loss will make generalizing performance predictions to every user difficult. The HIA has also committed to a 30-day trial period and remanufacture or replacement of new hearing aids if a customer is dissatisfied with their performance when they are coupled to a digital cell phone. If a customer remains dissatisfied with the hearing aid's performance, even after the aid has been remanufactured or replaced, a full refund will be provided.

The Rehabilitation Engineering Research Centers (RERCs) on Telecommunications Access and Hearing Enhancement have both been conducting field studies on cell phones and hearing aids since the problem was first identified. In the late 1990s, the RERCs performed a study on 53 hearing aid wearers and the usability of early digital cell phones [8]. This study found minimal problems with "bystander" interference from nearby cell phone users but severe interference problems during normal cell phone use for most of the sample; the majority of whom wore behind-the-ear (BTE) hearing aids.

In a later experiment, the RERCs determined the signal-to-interference ratios associated with usability levels as judged by 40 hearing aid wearers [9]. These findings, along with those of Srinivasan et al. [10] and Killon (see Preves [11]), were used to establish performance categories in the ANSI C63.19 standard [5].

After the FCC initiated a rulemaking on this issue, the RERC on Telecommunications Access conducted a new field study to determine the status of digital cell phone HAC based on commercially available products that were not identified by their manufacturers as HAC but that did support telecoil coupling.

METHODS

Data were collected during an SHHH national conference. Subjects were solicited for the study at the convention. The criteria for participation in the study were the following: must be between 18 and 70 years of age, must be daily hearing aid users, must use the telephone (rather than TTY or relay) for most of their calls, and must use a hearing aid whenever talking on the telephone. All persons tested were paid for their participation.

Twenty-one hearing aid wearers, ranging in age from 41 to 70, with an average age of 56, participated in the study. Characteristics of the sample are displayed in **Table 2**. Of the 21 participants, 3 were male and 18 female. Among the hearing aids worn by the participants, eight hearing aid manufacturers were represented. Fourteen participants wore BTE hearing aids and seven wore either in-the ear or in-the-canal aids. Three described their hearing loss in the better ear as severe-profound, and 18 reported hearing loss that ranged from moderate to severe. Six used conventional analog aids for the test, eight used digitally programmable aids, and seven used fully digital aids. A majority of the participants (15/21) had used their hearing aids for 5 years or less. Seventeen participants owned cell phones at the time of the test, and

Table 2.
Characteristics of participants.

Variable	*n*	%
Gender		
Female	18	83
Male	3	17
Hearing Loss Category		
Severe-Profound	3	17
Moderate-Severe	18	83
Style of Aid		
BTE	14	67
ITE or ITC	7	33
Technology in Aid		
Analog	6	29
Digitally Programmable	8	38
Fully Digital	7	33
Hearing Aid Mode Used in Evaluation		
Microphone	4	19
Telecoil	15	71
Both (tested twice)	2	10
Cell Phone Ownership		
Own Digital Cell Phone	12	57
Own Analog Cell Phone	5	24
No Cell Phone	4	19
Interference Experience		
Never Heard Interference from Cell Phone	3	17

BTE = behind the ear, ITC = in the canal, ITE = in the ear.

most of them (12/17) owned digital cell phones. Only three said they never heard interference when using their cell phones.

Four individuals used only microphone (acoustic) coupling, two individuals used both microphone and telecoil coupling, and 15 individuals used only telecoil (inductive) coupling. Data on 23 sets of ratings are included, since two participants provided ratings in both coupling modes.* Testing took place in a quiet room in the hotel that was away from convention activity. During each 1-hour session, participants completed a brief interview on their hearing status, hearing aid use, and telephone use. Prior to testing, participants were trained on a landline phone. We performed the training so participants would be familiar with the procedures for obtaining subjective data of their listening experience on a live call with each test phone and a baseline phone. The landline phone was used because it conformed to the RS-504 standard for magnetic-field strength; this ensured that telecoil users would be able to couple their hearing aids to the phone and complete the training. After training, participants completed the test procedure described below. While listening, all participants used their preferred ear and preferred mode of hearing aid-to-telephone coupling.

From each of the seven handsets that were evaluated, a live call was placed to a landline phone through which a recorded conversation between a male and a female speaker was played. The recording was long enough that no part of the conversation had to be repeated during the evaluation of the handsets. The transmission level of the recorded speech stimuli was set and monitored with a voltmeter to maximize the level of the speech without introduction of any unwanted distortion over the phone line.

For each participant, phone presentation order was randomized. An analog landline phone, which had a rotary-dial volume control and a G-style handset, was used as the baseline handset. The six digital cellular handsets in the study represented the three most common transmission technologies (code division multiple access [CDMA], GSM, and Integrated Digital Enhanced Network [iDEN]) and two form factors (flip and bar style). Characteristics of each handset are shown in **Table 3**. **Table 4** shows the service providers, as of March 2005, associated with each transmission technology tested.

*Five data points are missing because of data recording problems during testing.

Table 3.
Characteristics of handsets evaluated.

Handset	Transmission Technology	Shape of Handset (Form Factor)
1	Analog Landline	G-style
2	GSM	Bar-style
3	GSM	Flip-style
4	iDEN	Bar-style
5	iDEN	Flip-style
6	CDMA	Bar-style
7	CDMA	Flip-style

CDMA = code division multiple access, GSM = Global System for Mobile Communications, iDEN = Integrated Digital Enhanced Network.

Table 4.
Transmission technologies used by largest U.S. service providers as of April 2005.

Transmission Technology	Wireless/Cellular Carrier
CDMA	Verizon Wireless, Sprint PCS
iDEN	NexTel (recently acquired by Sprint)
GSM	Cingular Wireless (including former AT&T Wireless Services), T-Mobile

CDMA = code division multiple access, GSM = Global System for Mobile Communications, iDEN = Integrated Digital Enhanced Network.

The backlight on each phone's display was turned off, and the subject was given the phone. Subjects were instructed to adjust the volume of the phone and/or the gain control of their hearing aid to the most comfortable listening level for the recorded speech stimuli. Participants then indicated their ratings of each phone while they listened to the recorded conversation. Rating scales included loudness of the speech, speech intelligibility (on two different scales), annoyance from interference, overall sound quality of the signal received, and usability of the phone. In this article, results for ratings of loudness of speech and annoyance due to interference will be examined, as well as the relationships between usability, annoyance, and speech intelligibility ratings.

RESULTS

The first parameter that subjects were asked to rate was the loudness of the speech heard on the telephone. Loudness was rated on a 7-point rating scale, where higher scores indicated louder speech stimuli (1 = inaudible, 4 = comfortably loud, and 7 = too loud). Loudness ratings indicated that most subjects were able to achieve a level where speech was comfortably loud. However, both microphone and telecoil users tended to select maximum or near-maximum handset volume control settings to achieve comfortable listening levels.

Figures 1–2 show the distribution of participants' ratings of their annoyance because of interference, and the ratings are broken down according to the characteristics of the handsets represented in the study. **Figure 1** shows annoyance ratings for the landline control and the three common digital cellular transmission technologies (GSM, CDMA, and iDEN). Annoyance because of interference was rated on a 6-point rating scale; higher scores indicated more interference (0 = no interference, 3 = annoying interference, and 5 = unbearable interference). Since two handsets were rated for each transmission technology, there are approximately twice as many observations per technology as for the landline control, where only one handset was rated. The differences in the distribution of annoyance ratings for the three digital cellular transmission technologies were significant (Friedman χ_r^2 = 53.04, df = 2, p < 0.01). Pairwise Friedman's chi-square

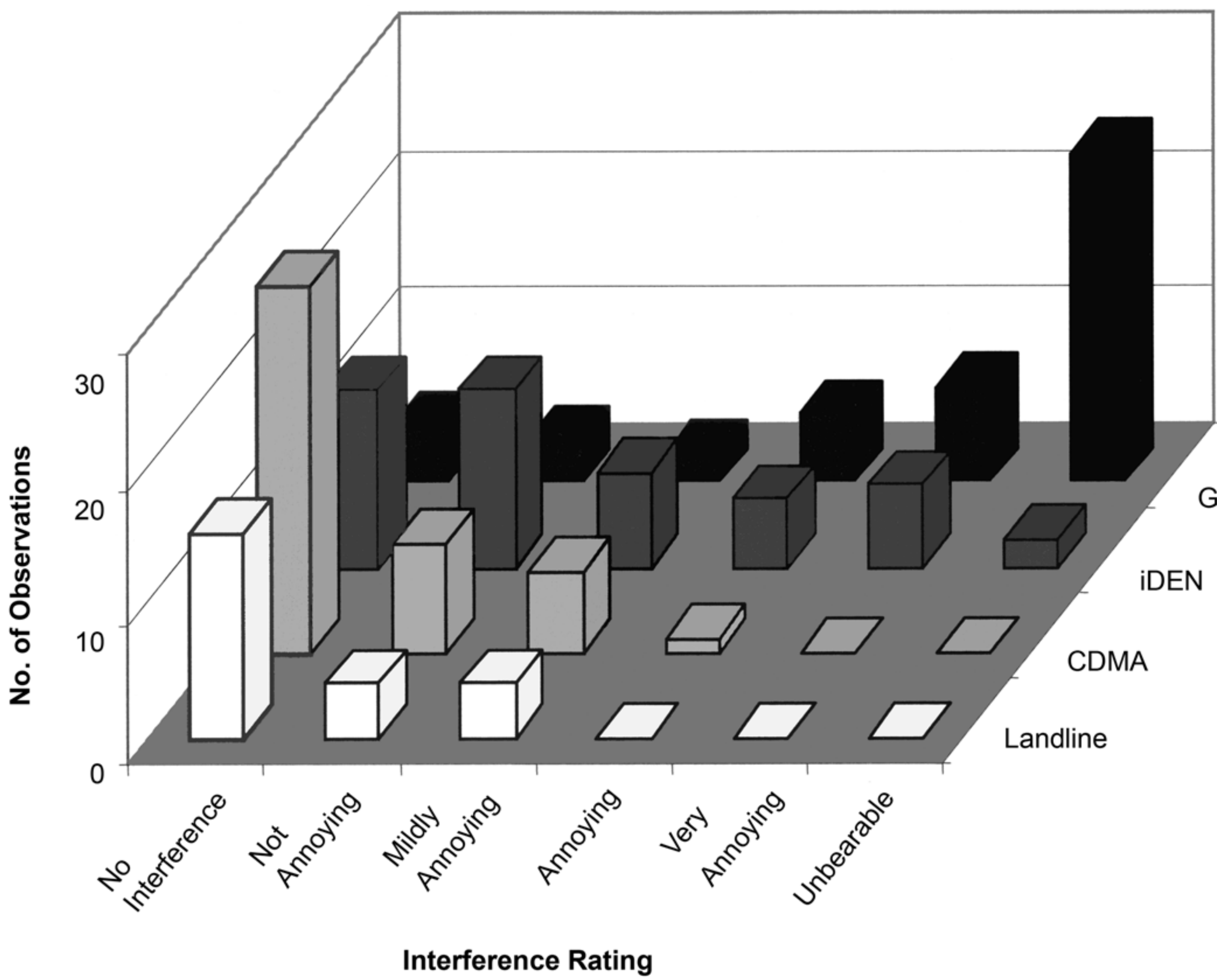

Figure 1.
Distribution of participants' annoyance rating of interference from landline control (n = 23) vs. three digital cellular transmission technologies (n = 42 for code division multiple access [CDMA], 46 for Integrated Digital Enhanced Network [iDEN], and 45 for Global System for Mobile Communications [GSM]).

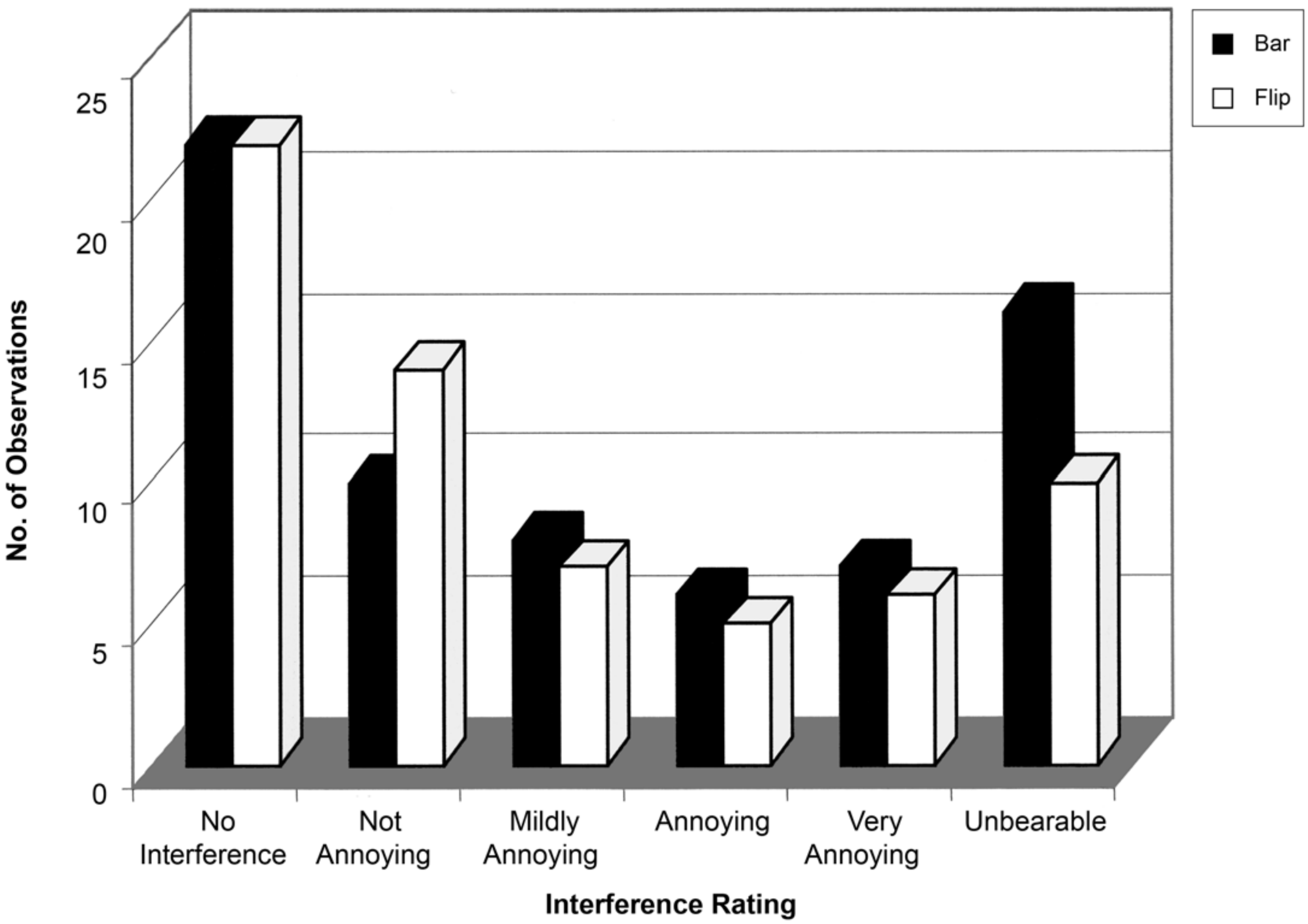

Figure 2.
Distribution of participants' annoyance rating of interference for bar-style (n = 69) and flip-style (n = 64) handsets across three digital cellular transmission technologies.

tests for repeated measures ($p < 0.01$) indicated the following—

- GSM handsets received the poorest annoyance ratings of the three technologies. More than half of the ratings indicated that the interference was "unbearable."
- CDMA handsets received the best annoyance ratings of the three technologies. More than half of the ratings indicated that "no interference" was heard. Ratings of CDMA handsets were similar to those of the analog landline control.
- iDEN handsets received poorer annoyance ratings for interference than CDMA and better annoyance ratings than GSM handsets. Ratings for these handsets were distributed across the annoyance rating scale.

The acoustic characteristics of the interference generated by these three technologies differ in both their spectral and temporal properties, and qualitatively they sound different to the listener. This likely affects the degree of annoyance reported by the hearing aid user.

Form factor (bar-style handset vs. flip-style handset, across all digital cellular transmission technologies) had a significant relationship with annoying interference (Friedman $\chi_r^2 = 7.53$, $df = 1$, $p < 0.01$); this result suggests that consumers try a flip-style handset in their search for an acceptable cell phone. The increased distance between a hearing aid and a flip-style phone's antenna and other electronics may reduce the effects of interference-causing emissions. As shown in **Figure 2**, the flip-style handsets used in this study received fewer "annoying" and "unbearable" ratings and more "not annoying" ratings than the bar-style handsets. The generalizability of these results must be viewed with caution since only three bar-style and three flip-style handsets were tested.

In **Figure 3**, annoyance ratings are presented for each hearing aid coupling mode (microphone vs. telecoil) across the three digital cellular transmission technologies. Coupling mode had a significant relationship with interference ratings ($\chi^2 = 11.55$, $df = 5$, $p < 0.05$). A greater proportion of telecoil than microphone users experienced annoying interference (ratings 2–5) across the test handsets. Among microphone users, only 7 percent of the total interference ratings were at levels of "very annoying" and "unbearable." Among telecoil users, about one-third of the total interference ratings were at these levels. One needs to bear in mind that this sample of hearing aid wearers had a small number of microphone users and more than twice as many telecoil users. Nonetheless, telecoils can be susceptible to magnetic emissions in addition to RF emissions, so the probability that telecoil users will experience more annoying interference is greater compared with microphone users, as was the case in this sample of hearing aid wearers.

The concept of "usability" is of interest since the ANSI C63.19 standard attempts to predict usability based on the measured emissions of handsets and immunity of hearing aids. **Figure 4** displays the relationship between annoyance ratings for interference and usability ratings

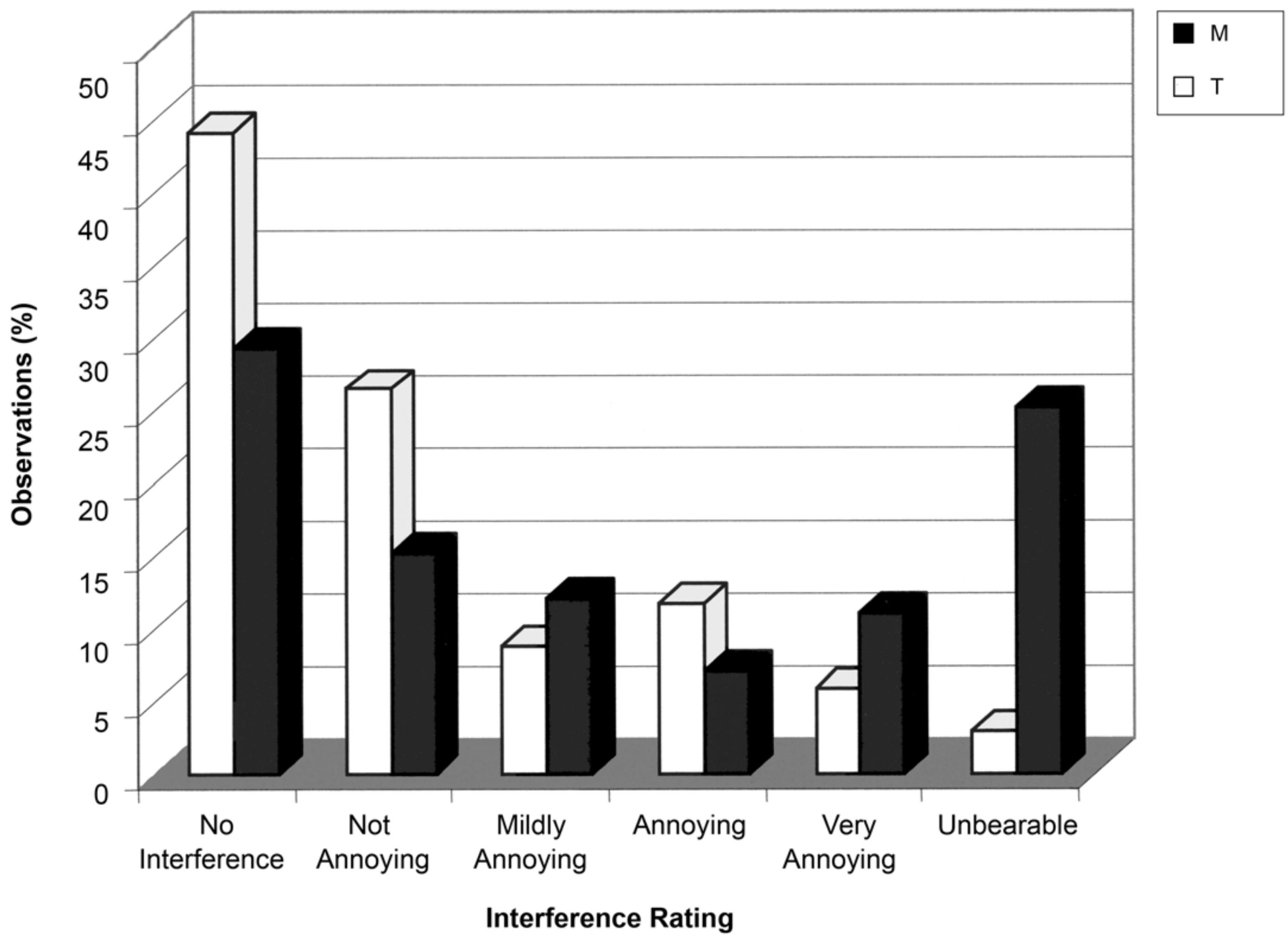

Figure 3.
Distribution of participants' annoyance rating of interference by hearing aid coupling mode (*n* = 34 for microphone [M] mode and 99 for telecoil [T] mode) across three digital cellular transmission technologies.

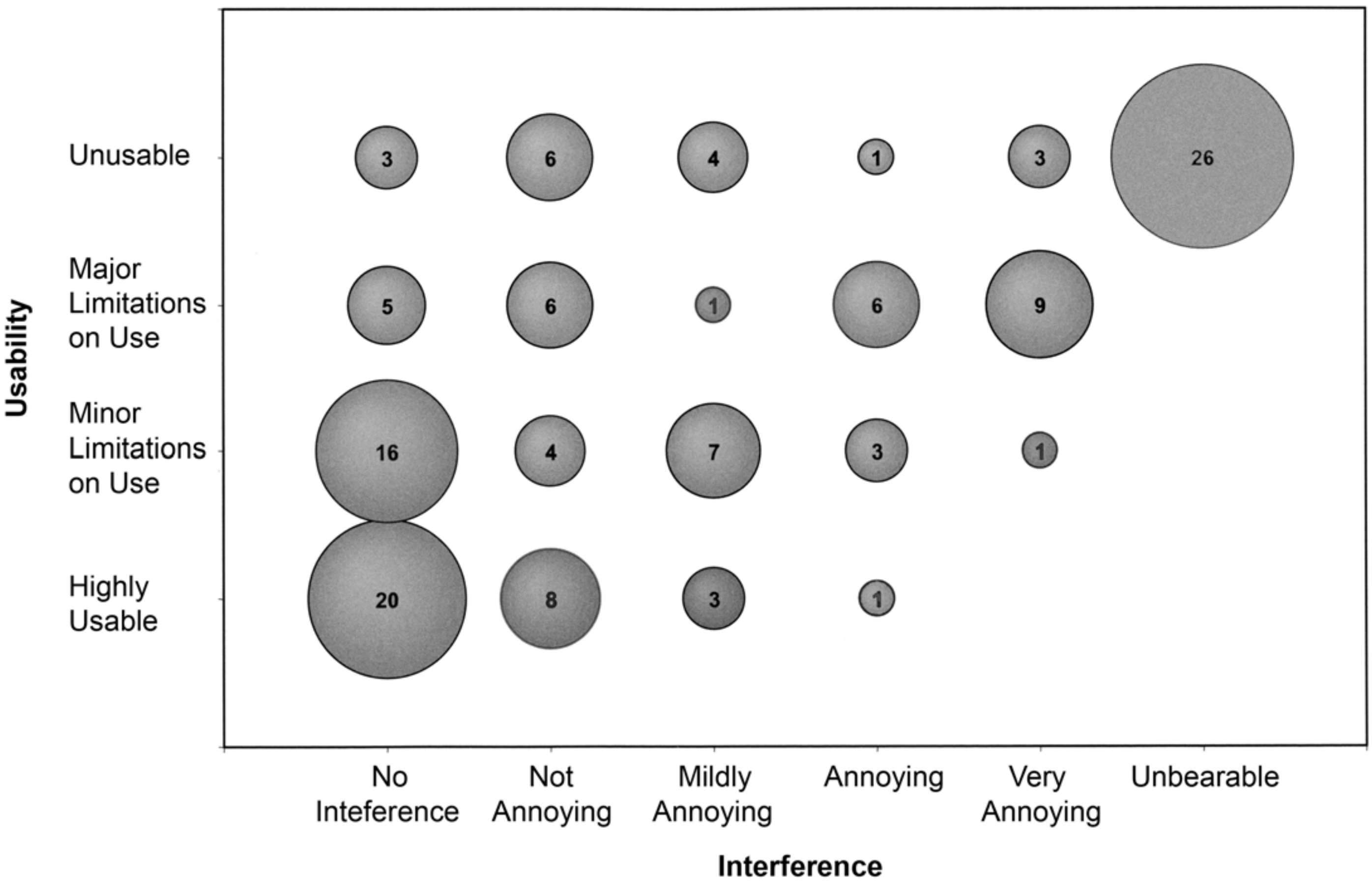

Figure 4.
Joint distribution of annoyance ratings for interference vs. usability across all six experimental conditions (n = 133). Value in each circle shows number of observations for particular usability rating as a function of a given interference rating.

across the six digital cellular handsets in this study. Where annoyance from interference was rated as high, the corresponding ratings on usability were uniformly low. However, where annoyance from interference was rated as low, the corresponding ratings of usability were distributed across all points on the scale from highly usable to unusable. The degree of correlation between the two variables, annoyance from interference vs. usability, was moderate at r^2 = 0.64.

This finding suggests that factors in addition to interference contribute to the hearing aid wearer's perception of usability. A stronger correlate of usability was the user's estimate of percent words understood. **Figure 5** displays the relationship between ratings for estimates of percent words understood vs. usability across the six digital cellular handsets in this study. The correlation between these two variables was high at r^2 = 0.88.

When interference from the handset dominates the auditory experience of the hearing aid user and not only produces annoyance but also reduces speech understanding, perceived usability may be driven primarily by the interference. However, when interference from the handset is absent or not annoying, other handset factors, such as signal strength and fidelity, may dominate the auditory experience of the hearing aid user and produce differences in perceived usability; this may depend to some degree on how the handset factors impact speech intelligibility.

DISCUSSION

The cellular telecommunications industry is currently working to implement the FCC cell phone HAC rule. A cooperative effort, sponsored by the Alliance for Telecommunication Industry Solutions, between cell phone

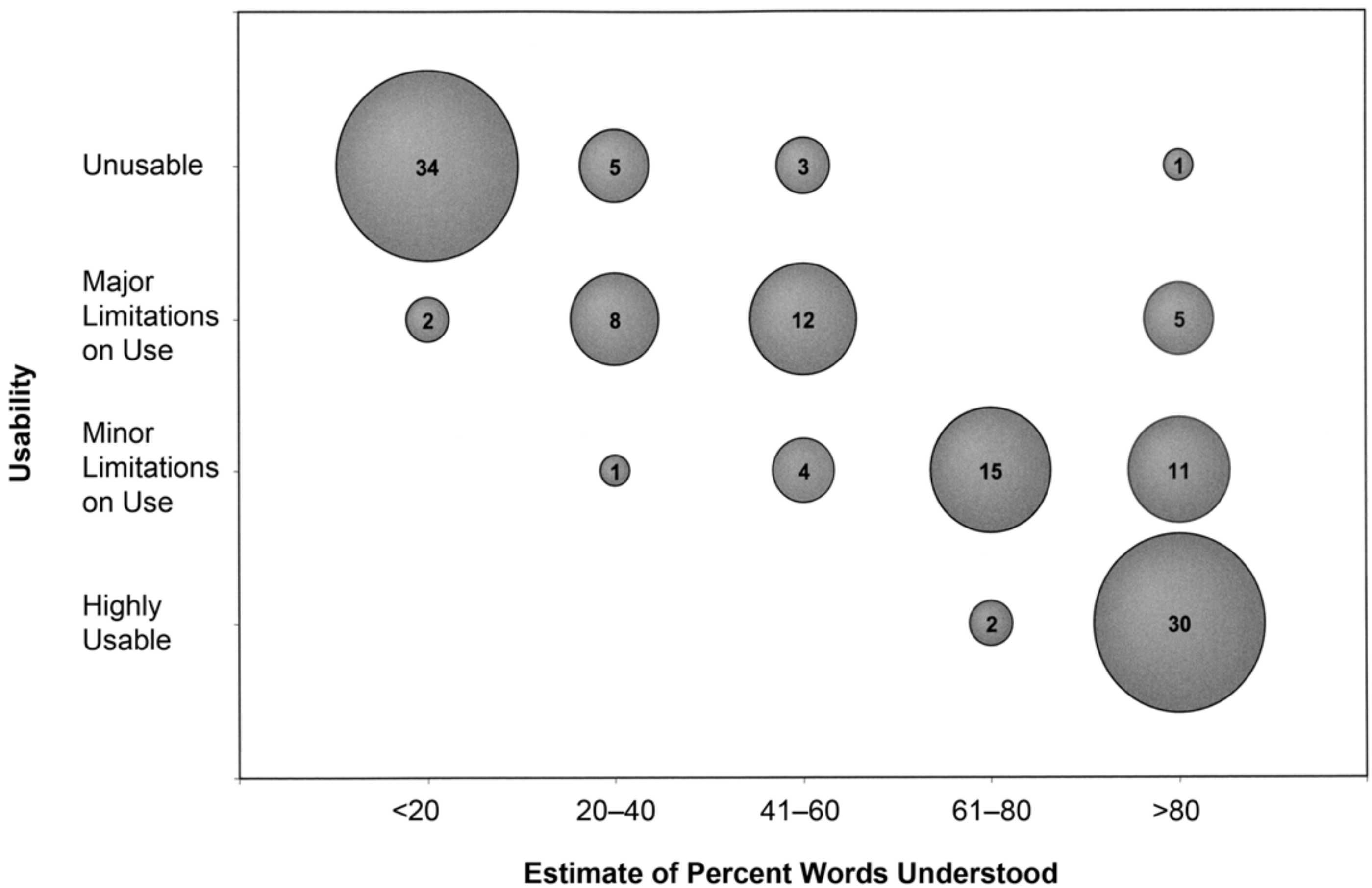

Figure 5.
Joint distribution of ratings for estimate of percent words understood vs. usability across all six experimental conditions (n = 133). Value in each circle shows number of observations for a particular usability rating as a function of a given estimate of percent words understood.

manufacturers, service providers, and the hearing aid industry is under way. The Institute of Electrical and Electronics Engineers, Inc., is currently revising the ANSI C63.19 standard to simplify and improve the reliability of measurement. The resulting standard may be different from the one in place at the time of the FCC rule. Changes to the standard that have been proposed since the FCC order was issued include changes in how cell phone emissions are measured for the telecoil rating; in particular, greater latitude in measurement location may be allowed. We plan to validate the revised testing procedure, when it is completed, by having the handsets used in this study tested under the new standard and correlating the results with user ratings.

The effectiveness of the rule will depend on users' experiences once handsets are rated and labeled. Based on the findings of this study, there is reason for concern that, without attention to handset factors other than interference that can influence the intended output of phones (i.e., speech), the hearing aid user's experience of usability may be lower than expected. This is of particular concern because the FCC ruling requires cell phones be labeled as well as an explanation of emission ratings in the product insert. Since the ANSI standard uses terminology for classifying cell phone and hearing aid performance that relates more to usability (i.e., excellent performance, normal use, usable but not acceptable for normal use) than to interference, consumer expectations may be inconsistent with their actual experience. A hearing aid wearer may use a hearing aid/cell phone combination that, based on the ANSI standard, should provide excellent performance, and even though the hearing aid wearer detects little to no interference, the performance of the two devices may be poor for other reasons, such as the audibility, perceived quality, or intelligibility of the speech that is heard.

Maximum or near-maximum handset volume control settings tended to be required by participants to achieve comfortable listening levels on the cellular handsets tested. Since testing was done in quiet listening conditions and the level of the speech signal was maximized for delivery over the landline network, the results suggest that attention needs to be paid to providing adequate volume control range on cellular handsets for hearing aid wearers. Unfortunately, the FCC ruling does not include volume control requirements with gain specifications as there are for corded and cordless phones. The ANSI C63.19 standard also does not address the acoustic output of the handset for hearing aid microphone coupling. Since usability was highly correlated with speech intelligibility, the acoustic output of the handset in the standard may be particularly important with regard to providing a uniformly high-fidelity signal across compatible handsets. For hearing aid telecoil coupling, the ANSI standard does specify field strength and frequency response requirements for the intended magnetic signal. The adequacy of these requirements is generally unknown.

Finally, backlighting was not active during the evaluations. Backlighting is a separate source of interference that is not addressed by the ANSI standard nor was it addressed in the present study. As such, it may contribute to user annoyance and discomfort if it cannot be turned on and off at will. We are working with the cell phone industry to determine which backlighting technologies cause interference in hearing aids.

CONCLUSIONS

This evaluation suggests that interference from digital cell phones continues to be problematic for hearing aid users, particularly those who use telecoil-to-telephone coupling. In addition, handsets that use GSM transmission technology are more likely to cause audible interference that is annoying to the hearing aid wearer than handsets that use either CDMA or iDEN transmission technologies. While annoyance from interference, particularly when it is high, can affect usability of the handset by hearing aid wearers, it is not the only factor that influences handset usability. The FCC rule is designed to guide hearing aid wearers to handsets that have a reduced likelihood of producing annoying interference when used with reasonably immune hearing aids. However, a compliant phone, while an important first step, does not necessarily guarantee usability of the cellular handset. Hearing aid wearers should still try cell phones before purchasing them to ensure finding the right cell phone for their individual hearing needs.

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