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The Benefit of Real-Time Captioning in a Mainstream Classroom as Measured by Working Memory

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The goal of this study was to determine if real-time captions benefit both students with normal hearing and students who are deaf or hard of hearing, and if the format of the display affects working memory. Working memory was measured with an established test that has been shown to be sensitive to perception difficulty.

Subjects who are deaf and subjects who are hearing were found to have similar abilities to recall written verbal material. Real-time captioning produced improved performance for both groups. Analysis of the real-time captioned conditions identified a significant effect for hearing type (hearing students performed 9.8% better than deaf students, $p < .05$) and the number of captioned lines (four lines were 4.3% better than two lines, $p < .05$) but not display location ($p > .60$). The conditions with four lines resulted in better performance than those with two lines, especially for the trials with larger memory demands.

Introduction

In the near future, speech recognition will progress to where portable and accurate processors will be feasible. One application of speech recognition will likely be personal captioning devices for people who are deaf or hard of hearing. This technology could be used to provide, for example, captions in classroom settings for students who are deaf. A variant of this device could include translation for foreign language students (both hearing and deaf).

A review of the research on captioning (Boyd & Vader, 1972; Gates, 1971; Murphy-Berman & Jorgensen, 1980; Nugent, 1983), suggests that a personal captioning device may improve performance. Furthermore, the literature suggests that captions are beneficial to hearing, learning disabled, and second-language students as well (Koskinen, Wilson, Gambrell, & Jensema, 1986; Markham, 1989; Neuman & Koskinen, 1992; Nugent, 1983; Seriwong, 1992).

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Real-time captioning is already used for news broadcasts and certain public speaking events. This method is rather expensive since a specially trained stenographer must be employed. In some cases, special equipment may also be necessary. For speaking events, the captions are usually placed over a video image of the speaker and projected onto a large screen. Students who are deaf or hard of hearing using such systems in college classrooms have indicated that real-time captions lead to greater understanding than manual interpreting (Stinson, Stuckless, Henderson, & Miller, 1988). In addition, these students rated hard copy transcripts to be more helpful than notes taken by assistants. However, due to high costs, this method is usually impractical for daily classroom activities at schools with small populations of students who are deaf or hard of hearing.

Simpler, personal devices are already being used as a low-cost option. In one application, a fast typist enters spoken material on a laptop computer. The text on the laptop screen appears as captions and is then saved as class notes (Everhart, Stinson, McKee, & Giles, 1996). Anecdotal comments indicate that while such arrangements are generally beneficial, counterproductive effects (e.g., drowsiness) may develop when students ignore the speaker, including non-verbal cues, in favor of the text (Smith, 1996). However, without further research it would be difficult to say that the negative effects were strictly due to the system and not some other factor (e.g., the lecture material). Computer-assisted notetaking systems attached to television monitors have also been used to provide real-time information (Youdelman & Messerly, 1996).

There has been little research on the effects of the location of the caption display, but there is work in related fields. Studies of navigation displays in the automotive field have shown that the proximity of the navigation display to the road scene is an important factor in effectiveness (Flannagan & Harrison, 1994; Green & Williams, 1992; Steinfeld & Green, 1998). In these studies, performance declined as the graphic display was moved away from the driver's view of the road. Other research identifies spatial proximity as one of the factors affecting performance in visual search tasks (Liu & Wickens, 1992).

The number of lines shown on a captioning display is usually based on trial and error, aesthetics, or the limitations of existing equipment. A study by Duchnicky and Kolers (1983) indicated that the number of lines presented on a cathode-ray tube affected reading speed (4 lines were faster to read than 1 or 2). These findings suggest similar results may be found in studies of real-time captioning.

Working memory "provides temporary storage and manipulation of the information necessary for such complex tasks as language comprehension, learning, and reasoning" (Baddeley, 1992; p. 556). The impact of captioning format on working memory is particularly important as working memory acts as the central processor for human reasoning. A test that measures functional working memory capacity was developed by Daneman and Carpenter (1980). In their study, a series of semantically independent sentences were

sequentially exposed to subjects. The subjects were asked to read or listen to sets of an increasing number of sentences and remember the last word of each sentence. At the completion of each set, the subjects reported the last words. This test becomes more difficult as the set size increases due to memory capacity limitations and decay. The ability to recall the last words is referred to as the "working-memory span." This measure was found to be strongly correlated to several verbal comprehension measures (e.g., a traditional paragraph reading comprehension test). A recent study by Daneman, Nemeth, Stainton, and Huelsmann (1995) found no significant differences in performance on working memory span tests between 5- to 14-year-old children who are deaf and who are hearing. This article also provides a discussion of working memory and additional findings of the working memory span test.

A captioning device is primarily a tool to support perception during communication. A reduction in the cognitive resources needed for perception should decrease working memory load and increase working memory span scores. In fact, Pichora-Fuller, Schneider, and Daneman (1995) demonstrated that it is possible to lower the working memory span score by making the stimuli more difficult to perceive.

The working memory span test is preferable to a traditional paragraph reading comprehension test. A major concern in comparing performance of subjects who are deaf with subjects who are hearing is the potential for significant differences in entry knowledge on traditional paragraph reading comprehension tests. For example, paragraphs that contain references to pop culture, music, or movies that were never captioned would likely place the subjects who are deaf at a disadvantage. The working memory span test increases objectivity, reduces subject testing time, and reduces stimulus fabrication costs.

While the working memory span test has been used in a variety of single information channel studies (e.g., reading cards), its ability to measure performance in a multiple channel scenario (text, voice, and lip motions) is uncertain. Thus, it was decided to compare performance on two baseline components (the speaker alone and the captions alone) to performance on the real-time captioned scenarios (a speaker with real-time captioning). The baseline scores approximate the reading and listening scores developed by Daneman and Carpenter (1980). If the scores from the real-time captioned (RTC) conditions correlated to the baseline scores, then it was deemed acceptable to use this method. Thus, a preliminary research question for this study was "Is the last-word method appropriate for testing real-time captioned scenarios?"

The key research question addressed by this study regarding effectiveness of the real-time captioning format was, "How do factors like location of display, number of lines, gender, and hearing ability impact the effectiveness of real-time captioning?"

Method

Participants

During recruitment, the participants were informed they would be watching videotapes in a classroom environment. All participants (12 college students) were paid volunteers. Of these 12, 6 were severely or profoundly deaf (mostly profoundly). The deaf students were all mainstreamed in university classes and were capable of interacting orally with the experimenter with only an occasional fingerspelled word. The pool included both undergraduate and graduate students (all fluent in English). Years of college experience and age were comparable across all groups except for the females who are deaf, who tended to have less experience than the rest of the subject pool. Recruiting students who are deaf was somewhat difficult due to the small population at the university.

As seen in Table 1, the students who are deaf reported being much more familiar with captioning than the students who are hearing (a rating of 0 being never, 5 all the time). The experience with interpreters was higher for the students who are deaf than for the students who are hearing, but only two students who are deaf rated their use of interpreters as being a 4 or 5. Additionally, one male who is deaf commented that, to the best of his knowledge, he was the only student at the university who had real-time captioning by a stenographer on a regular basis.

Apparatus

To maintain similarity to the experiment by Pichora-Fuller et al. (1995), sentences from the Speech Perception in Noise (SPIN) test (Kalikow, Stevens, & Elliot, 1977; Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1980) were chosen to be the stimulus material for this study. The sentences are provided in 8 forms of 50 sentences, where each form has a counterpart (see Table 2). Each counterpart has the same collection of last words. However, the last words have either "high" or "low" context based on the whole sentence. Each form has an equal amount of high and low context sentences, with the counterpart having the reverse context for each last word.

Six forms of 60 sentences each were made from the original 8 forms of 50 sentences each. To provide the additional 10 sentences, sentence pairs were randomly selected from the last 2 forms and added to the first 6. Semantic links between consecutive sentences were avoided. An equal number of high and low context last words were randomly positioned within each form. The forms were then broken into sets of 2, 3, 4, 5, and 6 sentences. There were 3 sets for each set size. The subsequent 15 sets for each form were ordered by increasing set size (2,2,2,3,3,3,4,4,4, etc.).

A special program written in SuperCard 2.5 was developed to scroll these sentence sets at a rate of 160 words per minute (a comfortable speaking speed). A videotape was recorded with the head and shoulders of a person

Table 1. Participant Information.

Hearing Type	Sex	Number	Mean Age (Years)	Years of College	Mean Rating of Experience w/ Captioning	Mean Rating of Experience w/ Interpreters
Deaf	Female	3	23.3	1.3	4.3	3.7
	Male	3	35	9.3	4.7	1.7
	All	3	27	5.3	4.5	2.7
Hearing	Female	3	27.7	7.2	.07	0.3
	Male	3	26.3	6.8	1.0	0.7
	All	3	29.8	7.0	0.8	0.5

Table 2. Sample sentences with context rating.

Examples From Form 1	
Sentence	Context
The old train was powered by steam.	High
He caught the fish in his net.	High
Mr. Smith knew about the bay.	Low

Examples From Form 2 (counterparts to Form 1)	
Sentence	Context
We have not discussed the steam.	Low
Paul should know about the net.	Low
The boat sailed across the bay.	High

(not the experimenter) reading the sentences at this rate. The speaker occupied the top two-thirds of the screen, while 4 lines of text scrolling at 160 wpm occupied the bottom third. The sentences were synchronized with the speaker so that the sentence would scroll up the moment the speaker finished the last word. The end result was the simulation of real-time captioning of a speaker with no time lag and no typing errors. Tapes were made of all 6 forms. Figure 1 shows a still from one of these tapes.

The tapes were shown to the subjects on a 33-inch color television and a 9-inch monitor. The television and monitor were placed in front of the subject at 72 and 27 inches respectively (equivlent perceived sizes for the text). The monitor was placed on the desk in front of the subject while the television was positioned on a cart against the blackboard. These locations simulated a student sitting in the first row of a classroom. The speaker appeared on the television in all but one condition (captions only). The image was approximately life size at a height similar to a speaker sitting on a stool. In the "podium" conditions, captions appeared on the television only as shown in Figure 1. For the "desk" conditions, the captions on the television were masked off with paper and shown on the desk monitor instead. The image of the speaker was always masked off on the desk monitor. Figure 2 shows the experiment set-up. The room was a small carpeted college seminar room with typical classroom ambient lighting and acoustics.

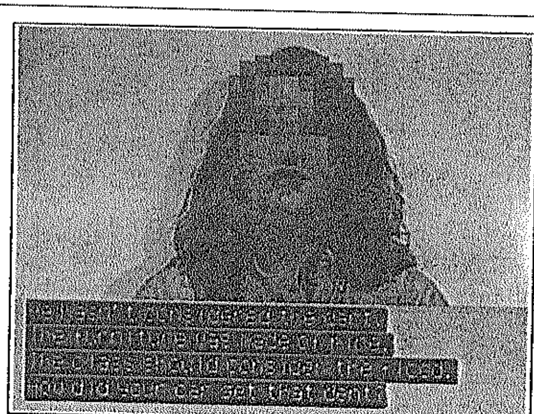

Figure 1. A still from one of the stimulus videotapes. (The speaker's face is not masked when the subjects view the tape.)

Procedure

Subjects were instructed on the tasks. The tasks were a working memory span test and a simple context decision task. First, they were asked to remember the last word for each sentence. Second, upon the completion of each sentence they were to raise their hand if the sentence had a high-context last word. The context decision was added to ensure that the subjects were reading the sentences and not just skimming the last words. Subjects were asked to write down the last words that they recalled upon the completion of each set. To provide practice, a four sentence set was presented to subjects using 3 x 5 inch cards, with one sentence per card. They were presented to the subject

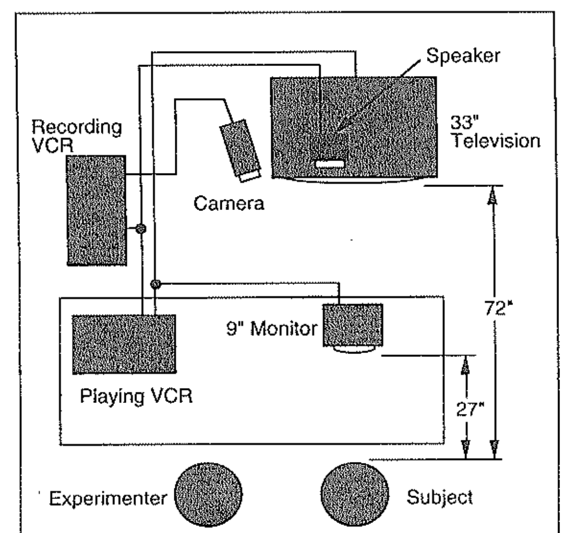

Figure 2. A plan view of the equipment layout.

and then replaced with the next card at a slow, steady rate. After this practice, the experimenter checked to make sure the subjects understood the tasks.

The subjects were then shown videotapes of six working memory span test conditions. These conditions were shown to the subjects in two ways. First the baseline conditions, audio with the speaker's face or captions only, were shown. Then the RTC conditions (combinations of the two baseline sources) were shown. Table 3 shows the six conditions used in this study. The captions only condition showed two lines of text at the podium location.

The subject pool was split into four subgroups based on gender and hearing ability. The baseline and RTC conditions were counterbalanced independently of each other within each subject subgroup. The baseline conditions were always run first. The six stimulus videotapes were counterbalanced over the six conditions. Thus, presentation condition was not linked to presentation stimulus.

One difference between the present study and the Daneman and Carpenter (1980) test was a pause after each set to ensure the subjects would have enough time to read the captions. The pause between the last spoken word and the scrolling up of two blank lines was consistent across all conditions so that every block would have the same memory decay times.

Following the completion of the working memory span tests, the subjects were asked to rank the six conditions in order of their preference. This provided structured information from the participants' subjective opinions.

Results

Is the last-word method appropriate for testing real-time captioned scenarios?

Words recalled were scored as accurate regardless of the tense the subjects wrote them in. Recall accuracy was calculated as a percentage of correct responses. The scores from the Daneman and Carpenter (1980) method were based on a different approach. The need for more resolution led to the measurement technique used in this study. The "Audio + Face" condition score for the hearing subjects is similar to the scores developed by Daneman and Carpenter (1980) using spoken material (listening memory span). The major alterations from the previous study were the addition of the speaker's face, the simple context decision, and a pause at the end of the presentation. It should be noted that the "Audio + Face" scores for the participants who are deaf measure memory spans that are confounded by the subject's ability to perceive oral information (speechreading with audio assistance). The "Captions Only" condition is a purer measure of memory span for the participants who are deaf. This is due to the higher probability of accurate perception (reading scrolled text as opposed to speechreading).

A repeated measures ANOVA comparing recall performance of the students who are hearing and those who are deaf over the "Captions Only" condition revealed no significant difference between the two groups ($p > .40$). This finding is important because it indicates that the two subject groups are similar when there are no perceptual differences.

Table 3. Conditions Examined.

Baseline Conditions	RTC Conditions
Audio + Face	Desk, 2 Lines
Captions Only	Desk, 4 Lines
	Podium, 2 Lines
	Podium, 4 Lines

Recall accuracy on the "Audio + Face," "Captions Only," and the mean scores across the RTC conditions were correlated. The relationship between "Captions Only" and mean RTC condition was found to have a strong, significant correlation (.83, $p < .001$). The relationship between "Audio + Face" and mean RTC condition was also significant (.76, $p<.01$). However, a plotted graph of the participants (Figure 3) revealed that performance on "Audio + Face" was cleanly split by hearing type, reflecting that results for this condition are confounded by the ability to perceive the information. The two baseline conditions were not significantly correlated.

Thus, performance on the RTC conditions is similar to performance under the more traditional working memory span tests (baseline conditions). This is especially true when performance on the RTC conditions is compared to the "Captions Only" condition. Therefore, the last-word method is appropriate for testing real-time captioned scenarios.

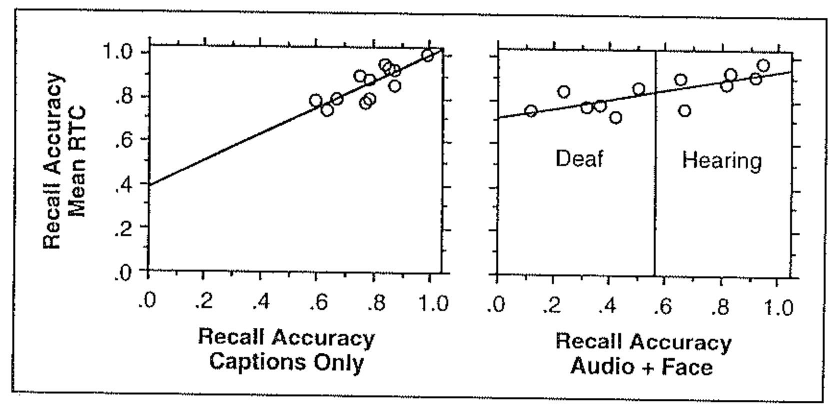

Figure 3. Comparisons of mean RTC condition to baseline conditions.

What factors affect perception of real-time captioned scenarios?

As shown in Figure 4, real-time captioning increased recall accuracy. In terms of performance, the two conditions with lowest accuracy for the hearing students were the baseline conditions ("Audio + Face" and "Captions Only"). The deaf participants displayed a remarkably low average score for the "Audio + Face" condition as they tried to speechread the person talking on the tape. Speechreading clearly incurs high perception and cognitive loads. In addition, there were probably many cases where the deaf participants could not even discern the words. This observed difficulty is most likely due to the fact that the sentences were short and not semantically linked. Thus, the presentation contained less context than typical conversations.

The suggestion of a uniform shift between the students who are deaf and the students who are hearing for the RTC conditions seen in Figure 4 hints that there may not be interaction effects for Hearing Type by Line Number or Hearing Type by Location. This suspicion proved accurate. A repeated measures ANOVA demonstrated that neither interaction was significant ($p > .6$ and $p > .3$, respectively). Further examination of Figure 4 suggests that there was a Line Number effect but not a Location effect. The ANOVA model found that this was indeed true.

Table 4 displays the ANOVA results and the factors used in the model. The Set Size factor in Table 4 refers to the number of last words the subjects were

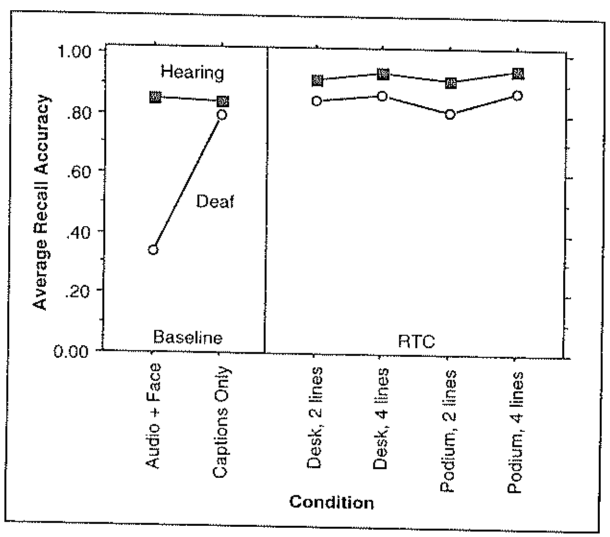

Figure 4. Performance as a function of condition and hearing type.

Table 4. ANOVA findings for recall accuracy.

	Main Effect	Interactions: Sex	Line Number	Location	Set Size
Hearing Type Deaf, Hearing	+				+++
Sex Female, Male					
Line Number 2,4	+			-	++
Location Desk, Podium					
Set Size 2,3,4,5,6	+++				

$p<.1$	$p<.05$	$p<.01$	$p<.001$
-	+	++	+++

asked to remember before writing them down. There were no significant 3-way interactions. Figure 5 shows the significant effect for Set Size and the interaction between Set Size and Hearing Type. Note that once the subject was exposed to more than three sentences, the curves depart from near 100% recall. It is readily apparent that the students who are deaf displayed a more rapid departure from 100% recall as the Set Size increased.

A pattern similar to that seen in Figure 5 was also apparent in the Set Size by Line Number interaction. For this case, sets sizes with two lines exhibited the more rapid departure from perfect recall. However, this interaction did not display differences as large as those seen in Figure 5.

Figure 6 displays the results of the subjects' mean preference rankings. The most interesting observation is that the trends are very similar to the memory results. The preference scores for each subject over each condition ($12 \times 6 = 72$ cases) were significantly correlated with the corresponding memory recall scores (.53, $p < .001$). It is possible that the subjects were aware of conditions in which they did well and set their preferences accordingly at the end of the experiment. Note that the baseline conditions are considered somewhat equal by the hearing subjects. This result is also similar to their memory scores.

Discussion

Real-time captions were a clear benefit for both the students who are hearing and the students who are deaf. The students who are hearing probably benefited from the increase in stimulus redundancy, as they were able to use both the speaker's voice and the captions. A 9.8% increase in recall accuracy was seen from a traditional presentation ("Audio + Face") to the RTC conditions for the hearing subjects. The decrease in perception difficulty was clearly beneficial to the students who are deaf, with a 149.6% increase from the "Audio + Face" condition to the RTC conditions. The real world impact of these findings is that providing captions will clearly help students who are deaf. In addition, the captions will also assist their hearing classmates. This is especially true for rooms with poor acoustics.

The two groups displayed similar reading working memory spans, as there was no significant difference between the groups for the "Captions Only" condition. The lack of a significant difference for hearing ability on this condition extends similar findings by Daneman et al. (1995) from children to the college population. In that study, degree of hearing loss did not affect reading memory span. Furthermore, the lack of significant interactions of display format factors with hearing ability across the RTC conditions lends merit to an earlier study which showed that hearing ability does not seem to affect one's ability to learn from captioned presentations (Nugent, 1983).

The amount the subjects were asked to remember (set size) was the only factor that interacted with hearing ability. Participants who are deaf departed

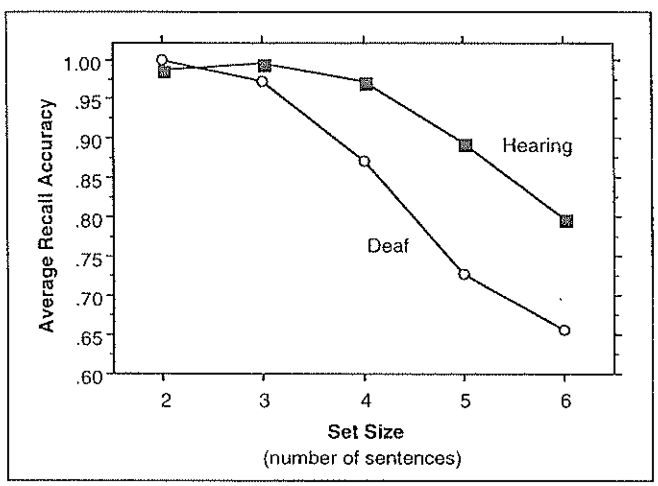

Figure 5. Performance as a function of Set Size and Hearing Type.

from 100% recall faster than hearing subjects for the RTC conditions. This difference is probably due to the greater degree of stimulus redundancy for the hearing students.

The analysis also found a strong effect for the number of captioned lines but no significant effect for display location. These findings are important because they suggest what type of device should be used. The two locations were picked to simulate a personal system housed in a laptop computer (desk) and a system installed in a classroom (podium). Since there was no significant difference, the particular needs of the user and organization can dictate the selection of equipment. It should be mentioned that this research did not include the measurement of non-verbal cue reception. It is possible that a desk location will lead to a reduction in the student's awareness of the speaker's body or facial gestures. Video recordings of the subject's faces were collected during this study. Analysis of these tapes may provide some preliminary findings on this topic.

The results clearly indicate that the equipment should display four lines of text. Scores on the four line conditions were 4.3% better than those for two lines. The reasons for this probably center on the larger buffer of information stored on the screen. A larger buffer allows the user to reread or slow down for difficult portions before the text scrolls off the screen. This result complements the findings of Duchnicky and Kolers (1983). Additionally, their work found no significant difference in reading speed between 4 and 20 lines; thus increasing beyond 4 may not be valuable. In fact, a greater number of lines may lead to longer search times when the student only needs a quick reference. However, the longer search times may be an acceptable sacrifice for an

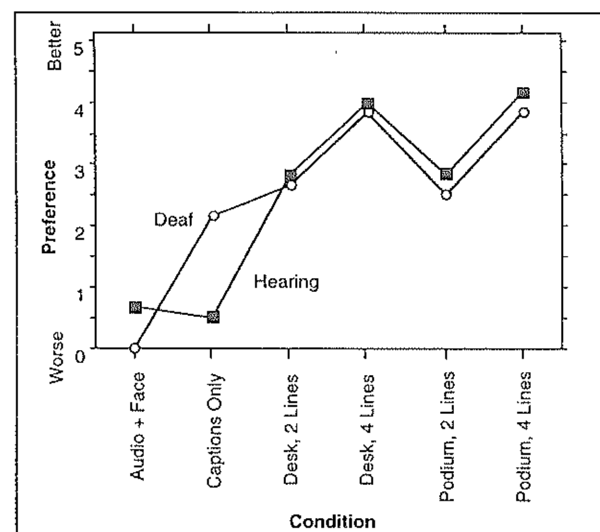

Figure 6. Preference ratings.

increased buffer of information. The question of whether to increase beyond 4 lines of text clearly needs more attention.

Another finding that suggests potential for future study is the correlation between performance and preference. A similar relationship was found by Steinfeld and Green (1998) in a study of navigational aids in automobiles. This suggests that the user may be able to subjectively determine the best interface option when given a set to evaluate. The degree to which a user's choice leads to optimal comprehension needs to be examined.

It should be noted that Daneman and Carpenter (1980) found that performance on the working memory span test correlated well with reading comprehension for both reading and listening tasks (from .42 to .86 at $p < .01$ or $p < .05$, depending on the test modality and the comprehension measures). Later studies showed that readers with high scores were also better able to recover from sentences with misleading context (Daneman & Carpenter, 1983). This research, in conjunction with the lack of a significant difference between subjects who are deaf and subjects who are hearing for the "Captions Only" condition, suggests that the two groups have similar capabilities to comprehend written material. Additionally, the current study reinforces other work (Duchnicky & Kolers, 1983) that suggests that format style cannot be ignored in RTC development and deployment.

In general, this work supports earlier findings that providing real-time captions improves comprehension for students who are deaf and students who are hearing. In addition, the placement of the display (desk or podium) does not seem to affect performance. Since the number of lines shown was important, real-time captioning displays should have at least four lines of text. These findings should help determine appropriate display methods for real-time captioning and ensure optimal application of current transcription and new speech recognition technologies.

Acknowledgments

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