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Research Article

Visual Contribution to Speech Perception: Measuring the Intelligibility of Animated Talking Heads

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Animated agents are becoming increasingly frequent in research and applications in speech science. An important challenge is to evaluate the effectiveness of the agent in terms of the intelligibility of its visible speech. In three experiments, we extend and test the Sumby and Pollack (1954) metric to allow the comparison of an agent relative to a standard or reference, and also propose a new metric based on the fuzzy logical model of perception (FLMP) to describe the benefit provided by a synthetic animated face relative to the benefit provided by a natural face. A valid metric would allow direct comparisons accross different experiments and would give measures of the benfit of a synthetic animated face relative to a natural face (or indeed any two conditions) and how this benefit varies as a function of the type of synthetic face, the test items (e.g., syllables versus sentences), different individuals, and applications.

1. INTRODUCTION

It is not surprising that face-to-face communication is more effective than situations involving just the voice. One reason is that the face improves intelligibility, particularly when the auditory signal is degraded by the presence of noise or distracting prose (see Sumby and Pollack [1]; Benoît et al. [2]; Jesse et al. [3]; Summerfield [4]). Given this observation, there is value in developing applications with virtual 3D animated talking heads that are aligned with the auditory speech (see Bailly et al. [5]; Beskow [6]; Massaro [7]; Odisio et al. [8]; Pelachaud et al. [9]). These animated agents have the potential to improve communication between humans and machines. Animated agents can be particularly beneficial for hard-of-hearing individuals. Furthermore, an animated agent could mediate dialog between two persons communicating remotely when their facial information is not available. For example, a voice in telephone conversations could drive an animated agent who would be visible to the participants (see Massaro et al.[10]; Beskow et al. [11]). An animated agent can also be used as a vocabulary tutor (see Bosseler and Massaro [12]; Massaro and Light [13]), a second language instructor (see Massaro and Light [14]), a speech production tutor (see Massaro and Light [15]), or personal agent in human-machine interaction (see Nass [16]).

Given that the effectiveness of animated agents is critically dependent on the quality of their visible speech (in this paper, we use the term "visible speech" to describe both physical and perceptual aspects of visible speech. Note that, for the physical signal, the term "optical signal" is also used in literature) and emotion, it is important to assess their accuracy. An obvious standard or reference for measuring this accuracy is to compare the effectiveness of an animated agent to that of a natural talker. We know that a natural face improves the intelligibility of auditory (in this paper, we use the term "auditory speech" to describe both physical and perceptual aspects of audible speech. Note that for the physical signal, the term "acoustic signal" is also used in literature) speech in noise and we can evaluate an animated agent relative to this reference (see Cohen et al. [17]; Massaro [7, Chapter 13], Siciliano et al. [18]). Given the individual differences in speech intelligibility of different talkers, the natural reference should be someone who provides high quality visible speech, or a sample of different talkers should be used. Following this logic, a defining characteristic of our research has been the empirical evaluation of the intelligibility of our visible speech synthesis relative to that given by a human talker with good visible speech. The goal of the evaluation process is to determine how the synthetic visual talker falls short of a natural talker and to modify the synthesis accordingly. It is also valuable to be able to contrast the effectiveness of two different animated agents or any two visible speech conditions, for example, a full face versus just the lips.

The goal of this paper is to facilitate the evaluation of the effectiveness of an agent in terms of the intelligibility of its visible speech. In their seminal study, Sumby and Pollack [1] demonstrated that speech intelligibility improved dramatically when the perceivers viewed the speaker's facial and lip movements relative to no view of the speaker. They also found that, as expected, performance improved in both conditions with decreases in vocabulary size. Sumby and Pollack [1] proposed a metric to describe the benefit provided by the face relative to the auditory speech presented alone. We define an *invariant metric* as one that gives a constant measure of the contribution of visible speech across all levels of performance, and therefore would be independent of the speech-to-noise ratio. It would also be valuable to have a measure of effectiveness that describes intelligibility relative to a reference. One of our goals is to extend the metric proposed by Sumby and Pollack [1] to describe the benefit provided by a synthetic animated face relative to the benefit provided by a natural face. The invariance of the metric describing the relative contribution of two visible speech conditions is tested in which auditory speech is presented under different noise levels and is paired with two different visible speech conditions. In three new experiments, we compare our synthetic talker Baldi to a natural talker, Baldi's lips only versus a full face, and a natural talker's lips only versus a full face. We can expect the overall noise level to greatly impact performance accuracy but an invariant metric describing the relative contribution of two visible speech conditions would remain constant across differences in performance accuracy. If some metric is determined to be invariant, it would allow direct comparisons across different experiments and would give measures of the benefit of a synthetic animated face relative to a natural face and how this benefit varies as a function of the type of synthetic face, the test items (e.g., syllables versus sentences), different individuals, and various applications.

2. TALKING HEAD EVALUATION SCHEME

The intelligibility of a synthetic talker system can be measured by a perceptual experiment with at least two conditions: unimodal auditory condition and bimodal audiovisual condition (e.g., Jesse et al. [3]). Typically, a set of utterances (syllables, words, or sentences) is presented to observers in a noisy environment that makes it difficult to perfectly understand the acoustic speech. The same acoustic signal is used in the unimodal and bimodal conditions, which are randomly interspersed during the test session. The noise should be loud enough to make it difficult to understand the auditory speech but not too loud to observe an improvement relative to the visible speech presented alone. More generally, a goal should be to have performance vary as much as possible across the different experimental conditions. A pretest might be needed to choose the best signal-to-noise levels for a given experiment. Participants are asked to recognize and report the utterances in the test. Massaro [7, Chapter 13] provides additional details about the choice of test items, the experimental procedure, and the data analysis of evaluation experiments. The difference between unimodal and bimodal conditions gives a measure of the benefit of the visible speech, and we will see that it is also valuable to present the visible speech alone.

2.1. Comparison of results across experiments

Multiple experiments are necessary to perform successive evaluations of the development of an animated agent. The initial intelligibility of the first instantiation of an animated agent cannot be expected to be optimal. Therefore, an intelligibility test should be performed by evaluating how much the animated agent facilitates performance relative to a reference, usually taken to be that given by a high-quality natural talker. By comparing the similarities and differences, these results can be used to create a new improved animated talker to be tested in a succeeding experiment. Similarly, evaluations of different agents from different laboratories or applications will also most likely be carried out in different experiments. In these two cases, it is difficult to make a direct comparison of the results of one experiment with another. One reason is that the participants, test items, and signal-to-noise levels will most likely differ across experiments, which would necessarily give different overall levels of performance. In many cases, the experiments will be carried out independently of one another, and even if they are not, it is practically very difficult to reproduce the accuracy level from one experiment to another. Thus, it is necessary to have an invariant metric that is robust across different overall levels of performance so that valid comparisons can be made across experiments.

2.2. Sumby and Pollack [1] visual contribution metric

To address this problem, Sumby and Pollack [1] proposed a visual contribution metric that was assumed to provide a measure that was independent of the noise level. This metric has been used by several researchers to compare results across experiments (see, e.g., LeGoff et al. [19]; Ouni et al. [20]). The metric is based on the difference between the scores from the bimodal and unimodal auditory conditions, and measures the visual contribution C_V to performance in a given *S/N* condition, which is

$$C_v = \frac{C_{AV} - C_A}{1 - C_A}, \quad (1)$$

where C_{AV} and C_A are the bimodal audiovisual and unimodal auditory intelligibility scores. In this formula, we expect C_{AV} to be greater than or equal to C_A. Given this constraint, as can be seen in (1), C_V can vary between 0 and 1.

Sumby and Pollack concluded that C_v is approximately constant over a range of speech-to-noise ratios. They stated, "*this ratio is approximately constant over a wide range of speech-to-noise ratios. Specifically, for the 8-word vocabulary, the ratio increases from about 0.81 at S/N ratio of −30 dB to about 0.95 at S/N ratio of −6 dB.*" Although Sumby and

Pollack [1] viewed this 14 difference as "approximately constant," we view it as a fairly substantial difference. Futhermore, the authors simply averaged results across individuals to compute these values, which could have reduced the variability across noise levels. Given the early date of this research, it is not surprising that no inferential statistics were computed to justify their conclusion that the relative visual contribution is independent of the noise level. Grant and Walden [21] showed problems with a related ANSI measure of performance by finding that the benefit of bimodal speech is inversely related to redundancy of the auditory and visible speech. Therefore, to the extent that varying the noise level systematically degrades some properties of the speech signal relative to others, then it is not reasonable to expect the Sumby and Pollack [1] metric or any measure that somehow computes the advantage of the bimodal condition compared to the auditory condition to give an invariant measure across noise levels. At the minimum, we would expect that the measure has to take into account not only the information in the auditory speech but also in the visible speech (see also Benoît et al. [2]).

3. RELATIVE VISUAL CONTRIBUTION METRIC

Sumby and Pollack's metric measures the contribution of a single talker. In our assessment of animated agents, the evaluation of an animated agent is made with respect to a natural talking head. A metric indicating the quality of an animated agent should be made relative to this reference of a natural talking head. A completely ineffective agent would give performance equal to or worse than the unimodal auditory condition and complete success would be the case in which the effectiveness of the animated agent would be equal to the reference. In the following, we introduce a modification of Sumby's formula, to give a direct measure of the effectiveness of an animated agent relative to that of a natural talker.

Equation (1) is based on the reference of perfect performance in the task. In evaluating animated agents, however, the reference is performance with a natural talking head. In practice, it is valuable to have several references of a natural talker but only one is used here because the main goal is to implement and test for an invariant metric. In the following, we introduce a metric that takes into account the natural talking head performance as the reference.

First, we start by introducing $\overline{C_v^r}$, the *relative visual deficit* to measure the missing information, that is, the gap between the visual contribution of the natural face and the visual contribution of the synthetic face. $\overline{C_v^r}$ is defined as follows:

$$\overline{C_v^r} = \frac{C_N - C_S}{1 - C_A}, \tag{2}$$

where C_S, C_A, and C_N are bimodal synthetic face, unimodal auditory, and bimodal natural face intelligibility scores.

We deduce from this equation the *relative visual contribution C_v^r*:

$$C_v^r = 1 - \frac{C_N - C_S}{1 - C_A}. \tag{3}$$

The validity of (3) requires that C_A is not one, which would then have division by zero. *The relative visual contribution C_v^r* in (3) is the contribution of the synthetic face relative to the natural face.

We can also write

$$C_v^r = 1 - \overline{C_r^r}. \tag{4}$$

It is easy to note that

$$C_v^r + \overline{C_v^r} = 1. \tag{5}$$

To use this metric meaningfully, the unimodal auditory recognition scores should not be perfect

$$0 < (1 - C_A) < 1. \tag{6}$$

If this inequality does not hold, it means that the unimodal auditory condition is not degraded and thus we cannot measure the benefit of visual speech. Thus, it is important in these experiments to add noise or degrade the acoustic signal channel by other means. We recall that the purpose of this metric is to evaluate the performance of a synthetic talker compared to a natural talker when the acoustic channel is degraded. We now describe how this measure should be interpreted.

3.1. *Interpretation of the relative visual contribution metric*

(1) $C_v^r > 1$

If $C_v^r > 1$, the synthetic face gives better performance than the natural face. This result could simply mean that the natural talker reference was below normal intelligibility, or that the visible speech was synthesized to give extraordinary information. Better performance for the synthetic face than the natural face can also be a case of a hyperrealism. The animation might have added additional cues not found in natural speech. For example, experiments have used so-called supplementary features to provide phonetic information that is not present on the face (see Massaro [7, Chapter 14], Massaro and Light [15]). These features can include neck vibration to signal voicing, making the nose red to signal nasality, and an air stream coming from the mouth to signal frication.

(2) $C_v^r \leq 1$

We expect that $C_v^r \leq 1$ will be the most frequent outcome because it has proven difficult to animate a synthetic talking face to give performance equivalent to that of a natural face. The value of C_v^r, however, provides a readily interpretable metric indexing the quality of the animated talker. The value of C_v^r is the visual contribution of the synthetic talker relative to that of a natural talker. For C_v^r, the value should be read as the visual contribution of the synthetic face compared to the natural face independently of the auditory conditions of degradation. For example, a value of 80% means the synthetic face reached 80% of the visual performance of the natural face. The quality of the animated speech approaches real visible speech as this measure increases from 0 to 1.

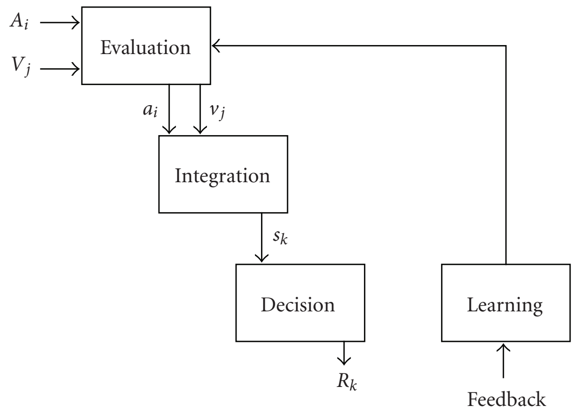


Figure 1: Schematic representation of the FLMP. The sources of information are represented by uppercased letters. Auditory information is represented by A_i and visual information by V_j. The evaluation process transforms these sources of information into psychological values (indicated by lowercased letters a_i and v_j). These sources are then integrated to give an overall degree of support s_k for each speech alternative k. The decision operation maps the outputs of integration into some response alternative R_k. The response can take the form of a discrete decision or a rating of the degree to which the alternative is likely. The learning process is also included. Feedback at the learning stage is assumed to tune the prototypical values of the features used by the evaluation process.

3.2. Fuzzy logical model of perception (FLMP)

One potential limitation of these two metrics is that they do not consider performance based on just the visual information. This is not unreasonable because visual alone trials are not always tested in experiments of this kind. Grant and colleagues (Grant and Seitz [23]; Grant et al. [24]; Grant and Walden [21, 25]) have included visual-only conditions, which have proved helpful in understanding the contribution of visible speech and how it is combined with auditory speech (see Massaro and Cohen [26]). We propose that much can be gained by including visual only trials.

The fuzzy logical model of perception (FLMP) can be used to assess the visual contribution to speech perception and therefore provide a measure of the relative visual contribution of the synthetic face relative to the natural (see Massaro [7]). Figure 1 is a schematic representation of the FLMP that illustrates three major operations in pattern recognition: evaluation, integration, and decision. The three perceptual processes are shown to proceed left to right in time to illustrate their necessarily successive but overlapping processing. These processes make use of prototypes stored in long-term memory. The sources of information are represented by uppercase letters. Auditory information is represented by A_i and visual information by V_j. The evaluation process transforms these sources of information into psychological values (indicated by lowercase letters a_i and v_j). These sources are then integrated to give an overall degree of support, s_k, for each speech alternative k. The decision operation maps the outputs of integration into some response alternative, R_k. The response can take the form of a discrete decision or a rating of the degree to which the alternative is likely. The learning process is also included in Figure 1. Feedback at the learning stage is assumed to tune the prototypical values of the features used by the evaluation process.

4. RELATIVE VISUAL CONTRIBUTION IN NOISE EXPERIMENTS

Given the potential value of this metric, it is important that it is demonstrated to be invariant. The critical assumption underlying the metric is that it remains constant with differences in unimodal auditory performance (of course, *ceteris paribis*, when all other experimental conditions are constant). To test this assumption, we carried out a first experiment comparing a natural talker against a synthetic animated talker, Baldi, at 5 different noise levels to modulate baseline performance. We chose a natural talker who has highly intelligible visible speech (see Bernstein and Eberhardt [22]; Massaro [7]). Then we carried out a second and third experiments comparing a full face to just the lips to provide additional results to test for an invariant metric. For instance, in addition to comparing a natural talker to a synthetic talker, the metric can be used to assess how informative a particular part of the face compared to another part or to the full face is. This type of result would be helpful in improving a particular part of the synthetic talker, for example. The conditions were chosen to give substantial performance differences between the reference and the test.

4.1. Method

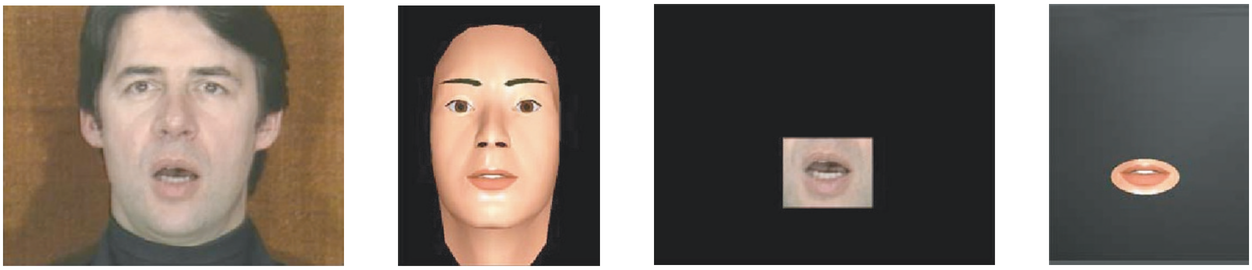
We carried out three expanded factorial experiments. In the first experiment, the five presentation conditions were: (a) unimodal auditory; (b) unimodal synthetic talker Baldi; (c) unimodal natural talker; (d) bimodal synthetic talker Baldi (the test); and (e) bimodal natural talker.

Participants

Thirty-eight native English speakers, from the undergraduate Psychology Department participant pool at the University of California at Santa Cruz participated in this experiment as an option to fulfill a course requirement in psychology. In the first experiment, ten participants were 18 to 20 years old in age, 5 females and 5 males. They all reported normal hearing and normal seeing abilities. Two participants spoke Spanish in addition to native English and one participant spoke Cantonese/Mandarin Chinese in addition to native English. All participants were right handed. There were 8 and 20 participants in Experiments 2 and 3, respectively, who volunteered from the same community as those in Experiment 1.

Test stimuli

The stimuli were 9 consonants: $C = \{/f/, /p/, /l/, /s/, /\int/, /t/, /\theta/, /r/, /w/\}$ and 3 vowels: $V = \{/a/, /i/, /u/\}$ to form a total of 27 consonant-vowel syllables (CVs). The consonant and vowel stimuli were chosen because they were



(a) (b) (c) (d)

Figure 2: Views of the natural talker, from the Bernstein and Eberhardt [22] videodisk, Baldi, and the two conditions of just the lips. In the first experiment, we presented the natural talker's full face and Baldi's full face. In the second experiment, we presented Baldi's full face and Baldi's lips only. In the third experiment, we presented the natural talker's full face and his lips only.

representatives of distinct consonant viseme categories. The acoustic signal was paired with 5 different white noise signals. The average values of the speech-to-noise ratio were: -11 dB, -13 dB, -16 dB, -18 dB, and -19 dB (which we refer to in the text as the *five noise levels*). There were also five presentation conditions: auditory only, visual-only natural talker, visual-only synthetic talker, bimodal natural talker, and bimodal synthetic talker. Thus, for each experiment, we had 27 stimuli per condition, 5 presentation conditions, and 5 noise levels. The 27 CVs were factorially combined with the five noise levels and three of the presentation conditions for $27 \times 5 \times 3 = 405$ trials. The 27 CVs were also presented under the two visual-only conditions to give 54 additional trials. Therefore, the total number of trials was 459 presented in a random order.

The natural speaker is shown in Figure 2, a male talker Gary (see Bernstein and Eberhardt laser videodisk [22]). His presentations were video clips, AVI files converted and extracted from the disk. The synthetic talker also shown in Figure 2 was Baldi, our computer-animated talking head.

The visual portions of the stimulus, that is, Baldi and the natural face, were presented at the same visual angle of approximately 30 degrees. The player used was our custom *PSLmediaPlayer* positioned at $200x$ $30y$ (from top left) and 640*480 size. The screen resolution was set to 1024*768 pixels. The auditory speech was taken from Gary's auditory/visual corpus of bimodal consonant-vowel syllables presented in citation speech. For the synthetic face, the visual phonemes were viterbi aligned and manually adjusted to match Gary's phonemes pronunciation. Participants were instructed to identify each test stimulus as one of the 27 consonant-vowel syllables.

Apparatus

The stimuli were presented using a software program built using rapid application design (RAD) tools from the Center for Spoken Language Understanding (CSLU) speech toolkit (http://cslu.cse.ogi.edu/toolkit/). The hardware was a PC running the *Windows* 2000 operating system with *Open-Gl* video card, 17 inch video monitor, and sound blaster audio. All of the experimental trials were controlled by the CSLU toolkit RAD application.

The second and third experiments had exactly the same design as the first experiment except that the test and reference conditions differed. In Experiment 2, Baldi was designated as the reference condition and a presentation of just his lips was the test condition. The third experiment was identical to the second except that the natural talker Gary from the Bernstein and Eberhardt [22] videodisk was used as the reference and just his lips was the test condition. Figure 2 presents views of the natural talker, Baldi, and the two corresponding conditions of just the lips.

4.2. Results

Figure 3 plots the overall percentage correct identification as one of the 27 CV syllables in the first experiment across five noise levels in the three conditions: unimodal auditory, bimodal AV-synthetic face, and bimodal AV-natural face. As can be seen in this figure, performance improved with decreases in noise level. Both the natural talker and Baldi gave a large advantage relative to the auditory condition. As expected, performance for Baldi fell somewhat short of that for the natural talker.

Figures 4 and 5 plot the overall percentage correct identification as one of the 27 CV syllables in the second and third experiments, respectively. Performance improved with decreases in noise level, both the full face and just the lips gave a large advantage relative to the auditory condition. For both the natural and synthetic talkers, the full face gave better performance than just the lips, although, the difference was much smaller for the natural face.

4.3. Test of Sumby and Pollack [1] visual contribution metric

In order to test whether the Sumby and Pollack [1] performance metric remains constant across the five levels of noise, the results for each subject in each experiment were pooled across identification performance on the 27 syllables to give overall performance accuracy for each subject

Table 1: Overall accuracy scores for each participant under each of the 15 conditions of Experiment 1. The last two columns present unimodal visual results.

	Unimodal auditory across 5 noise levels					Bimodal synthetic face across 5 noise levels					Bimodal natural face across 5 noise levels					Unimodal visual	
Participants	−19 dB	−18 dB	−16 dB	−13 dB	−11 dB	−19 dB	−18 dB	−16 dB	−13 dB	−11 dB	−19 dB	−18 dB	−16 dB	−13 dB	−11 dB	Synthetic	Natural
1	0.07	0.15	0.19	0.48	0.44	0.52	0.52	0.63	0.67	0.63	0.67	0.85	0.74	0.78	0.81	0.33	0.48
2	0.07	0.19	0.19	0.26	0.56	0.48	0.44	0.67	0.67	0.78	0.81	0.78	0.78	0.96	0.93	0.52	0.74
3	0.19	0.04	0.26	0.41	0.44	0.56	0.52	0.48	0.63	0.78	0.59	0.70	0.67	0.89	0.81	0.44	0.74
4	0.19	0.26	0.30	0.48	0.48	0.63	0.52	0.59	0.74	0.85	0.70	0.63	0.67	0.81	0.93	0.56	0.59
5	0.11	0.22	0.22	0.33	0.56	0.74	0.59	0.81	0.93	0.85	0.78	0.81	0.78	0.85	0.89	0.59	0.70
6	0.26	0.22	0.26	0.44	0.48	0.67	0.59	0.59	0.59	0.81	0.59	0.59	0.74	0.78	0.81	0.48	0.56
7	0.26	0.11	0.15	0.48	0.70	0.56	0.48	0.74	0.70	0.74	0.89	0.85	0.85	0.93	0.93	0.67	0.85
8	0.15	0.11	0.33	0.30	0.56	0.52	0.63	0.67	0.70	0.67	0.74	0.67	0.81	0.93	0.89	0.59	0.56
9	0.19	0.22	0.19	0.41	0.30	0.52	0.63	0.78	0.78	0.63	0.78	0.56	0.81	0.74	0.89	0.52	0.67
10	0.19	0.30	0.19	0.37	0.48	0.48	0.59	0.63	0.67	0.70	0.59	0.56	0.59	0.59	0.81	0.52	0.67
Mean	0.17	0.18	0.23	0.40	0.50	0.57	0.55	0.66	0.71	0.74	0.71	0.70	0.74	0.83	0.87	0.52	0.66

Table 2: Overall accuracy scores for each participant under each of the 15 conditions of Experiment 2. The last two columns present unimodal visual results.

	Unimodal auditory across 5 noise levels					Bimodal synthetic lips across 5 noise levels					Bimodal synthetic face across 5 noise levels					Unimodal visual	
Participants	−19 dB	−18 dB	−16 dB	−13 dB	−11 dB	−19 dB	−18 dB	−16 dB	−13 dB	−11 dB	−19 dB	−18 dB	−16 dB	−13 dB	−11 dB	Lips	Face
1	0.07	0.04	0.30	0.26	0.41	0.41	0.37	0.56	0.56	0.70	0.41	0.52	0.70	0.74	0.74	0.41	0.48
2	0.00	0.19	0.11	0.22	0.37	0.37	0.33	0.41	0.70	0.67	0.52	0.41	0.44	0.78	0.63	0.41	0.33
3	0.07	0.07	0.00	0.26	0.11	0.15	0.15	0.11	0.30	0.26	0.19	0.22	0.30	0.22	0.37	0.15	0.19
4	0.11	0.04	0.26	0.19	0.44	0.44	0.37	0.44	0.67	0.70	0.41	0.48	0.56	0.59	0.67	0.48	0.52
5	0.04	0.15	0.15	0.30	0.52	0.22	0.26	0.37	0.52	0.44	0.33	0.33	0.48	0.56	0.63	0.19	0.41
6	0.04	0.00	0.19	0.26	0.41	0.48	0.52	0.48	0.52	0.74	0.52	0.67	0.81	0.70	0.85	0.59	0.52
7	0.04	0.04	0.19	0.22	0.44	0.15	0.37	0.56	0.56	0.48	0.44	0.48	0.56	0.48	0.74	0.30	0.44
8	0.04	0.07	0.07	0.22	0.37	0.15	0.26	0.26	0.56	0.52	0.22	0.41	0.48	0.56	0.59	0.30	0.30
Mean	0.05	0.08	0.16	0.24	0.38	0.30	0.33	0.40	0.55	0.56	0.38	0.44	0.54	0.58	0.65	0.35	0.40

at each of the 15 experimental conditions of 3 presentation conditions times 5 noise levels. Thus, each of these 15 proportions for each participant had 27 observations. Tables 1, 2, and 3 give the overall accuracy scores for each participant under each of the 15 conditions for Experiments 1, 2, and 3, respectively. These proportions were used to compute both Sumby and Pollack's [1] metric (1) for both the synthetic face and the natural face and our derived metric for the relative visual contribution (3). Tables 4, 5, and 6 give Sumby and Pollack's [1] metric (1) for both the test and reference conditions for each participant across the three experiments, respectively. An analysis of variance was carried out on these scores with participants, experiments, and noise level as factors. The Sumby and Pollack formula, given by (1), tended to vary significantly across noise level for both the test case, $F(4, 140) = 3.21$, $p < 0.015$; and the reference case, $F(4, 140) = 11.62$, $p < 0.001$. This significant difference as a function of noise level violates the assumption that the Sumby and Pollack metric should be independent of the overall level of performance. The interaction of noise level with experiment was not significant.

4.4. Test of the relative visual contribution metric

Tables 4, 5, and 6 also give our metric for the relative visual contribution (3). In contrast to the Sumby and Pollack metric, however, our relative visual contribution metric did not differ over noise levels, $F(4, 140) = 0.89$. Nor did noise level interact with experiments, $F(8, 140) = 0.88$. It is somewhat surprising that our derived metric, which is based on the Sumby and Pollack metrics of the test and reference conditions, remained invariant across noise levels whereas the Sumby and Pollack metrics did not. Even so, the invariance of the derived metric is promising. We now turn to a new type of analysis that incorporates performance in the visual-only conditions.

5. EVALUATION BASED ON THE FUZZY LOGICAL MODEL OF PERCEPTION (FLMP)

As described in Section 4.1, a speechreading condition was actually included in the experiments: 27 CVs for the synthetic face and 27 for the natural. If the FLMP gives a good description of the observed results, its parameter values can be used to provide an index of the relative visual contribution. One of

Table 3: Overall accuracy scores for each participant under each of the 15 conditions of Experiment 3. The last two columns present unimodal visual results.

	Unimodal auditory across 5 noise levels					Bimodal natural lips across 5 noise levels					Bimodal natural face across 5 noise levels					Unimodal visual	
Participants	−19 dB	−18 dB	−16 dB	−13 dB	−11 dB	−19 dB	−18 dB	−16 dB	−13 dB	−11 dB	−19 dB	−18 dB	−16 dB	−13 dB	−11 dB	Lips	Face
1	0.07	0.11	0.07	0.19	0.52	0.52	0.52	0.59	0.85	0.67	0.70	0.67	0.67	0.85	0.85	0.56	0.56
2	0.11	0.04	0.19	0.30	0.56	0.52	0.59	0.48	0.56	0.70	0.48	0.63	0.63	0.70	0.78	0.44	0.59
3	0.04	0.11	0.22	0.44	0.33	0.56	0.44	0.52	0.63	0.63	0.52	0.56	0.67	0.81	0.74	0.44	0.44
4	0.00	0.22	0.11	0.37	0.52	0.59	0.63	0.74	0.81	1.00	0.63	0.78	0.81	0.85	0.89	0.52	0.74
5	0.04	0.11	0.26	0.30	0.37	0.67	0.67	0.74	0.78	0.89	0.74	0.67	0.81	0.85	0.96	0.52	0.56
6	0.22	0.15	0.19	0.41	0.52	0.56	0.56	0.78	0.81	0.81	0.63	0.67	0.70	0.78	0.81	0.59	0.48
7	0.15	0.11	0.26	0.52	0.59	0.70	0.63	0.78	0.78	0.89	0.74	0.74	0.81	0.74	0.85	0.74	0.70
8	0.15	0.11	0.26	0.48	0.63	0.67	0.70	0.74	0.93	0.85	0.74	0.63	0.81	0.93	0.93	0.70	0.63
9	0.11	0.15	0.11	0.26	0.33	0.56	0.63	0.63	0.59	0.81	0.63	0.63	0.81	0.89	0.74	0.52	0.63
10	0.15	0.07	0.30	0.33	0.44	0.70	0.59	0.67	0.85	0.93	0.70	0.74	0.63	0.89	0.89	0.67	0.59
11	0.11	0.26	0.11	0.52	0.52	0.78	0.70	0.63	0.93	0.96	0.74	0.85	0.81	0.89	1.00	0.63	0.81
12	0.19	0.11	0.22	0.48	0.44	0.59	0.74	0.78	0.67	0.85	0.74	0.70	0.74	0.85	0.89	0.70	0.85
13	0.11	0.07	0.11	0.33	0.56	0.56	0.48	0.59	0.78	0.81	0.56	0.48	0.67	0.78	0.93	0.56	0.56
14	0.11	0.11	0.15	0.33	0.41	0.70	0.67	0.78	0.85	0.93	0.70	0.78	0.70	0.93	0.89	0.70	0.70
15	0.07	0.07	0.19	0.30	0.44	0.44	0.70	0.67	0.63	0.74	0.63	0.67	0.67	0.78	0.85	0.48	0.59
16	0.11	0.04	0.11	0.48	0.33	0.74	0.81	0.70	0.78	0.85	0.70	0.81	0.93	0.93	0.85	0.74	0.74
17	0.07	0.07	0.19	0.30	0.44	0.44	0.70	0.67	0.63	0.74	0.63	0.67	0.67	0.78	0.85	0.48	0.59
18	0.07	0.15	0.07	0.37	0.56	0.52	0.52	0.67	0.81	0.70	0.67	0.70	0.74	0.85	0.89	0.52	0.63
19	0.11	0.19	0.30	0.44	0.59	0.70	0.81	0.85	0.93	0.93	0.78	0.85	0.78	0.85	0.93	0.63	0.70
20	0.11	0.15	0.19	0.52	0.44	0.67	0.85	0.78	0.89	0.81	0.52	0.67	0.70	0.89	0.89	0.63	0.63
Mean	0.11	0.12	0.18	0.38	0.48	0.61	0.65	0.69	0.77	0.83	0.66	0.70	0.74	0.84	0.87	0.59	0.64

Table 4: Sumby and Pollack's [1] metric (1) for both the synthetic face and the natural face and our metric for the relative visual contribution (3) for each participant in Experiment 1.

	Visual contribution of the synthetic face across 5 noise levels (1)					Visual contribution of the natural face across 5 noise levels (1)					Relative visual contribution across 5 noise levels (3)				
Participants	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	0.44	0.44	0.56	0.41	0.34	0.65	0.82	0.69	0.61	0.66	0.80	0.61	0.87	0.80	0.68
2	0.44	0.40	0.61	0.50	0.54	0.76	0.76	0.74	0.95	0.85	0.68	0.63	0.87	0.55	0.69
3	0.53	0.50	0.36	0.45	0.65	0.56	0.69	0.59	0.84	0.70	0.97	0.81	0.77	0.61	0.95
4	0.54	0.41	0.45	0.54	0.73	0.63	0.54	0.55	0.66	0.88	0.91	0.86	0.89	0.88	0.86
5	0.72	0.49	0.76	0.90	0.69	0.76	0.73	0.72	0.79	0.77	0.96	0.77	1.04	1.11	0.92
6	0.61	0.54	0.49	0.31	0.68	0.52	0.54	0.68	0.63	0.68	1.09	1.00	0.81	0.68	1.00
7	0.72	0.49	0.76	0.90	0.69	0.76	0.73	0.72	0.79	0.77	0.96	0.77	1.04	1.11	0.92
8	0.50	0.60	0.53	0.57	0.37	0.73	0.65	0.73	0.90	0.79	0.77	0.96	0.80	0.67	0.58
9	0.46	0.52	0.68	0.67	0.47	0.75	0.48	0.77	0.61	0.84	0.71	1.04	0.91	1.06	0.63
10	0.36	0.49	0.56	0.48	0.42	0.49	0.46	0.53	0.37	0.63	0.86	1.04	1.04	1.11	0.79
Mean	0.53	0.49	0.58	0.57	0.56	0.66	0.64	0.67	0.71	0.76	0.87	0.85	0.90	0.86	0.80

the best methods to test bimodal speech perception models, as well as examining the psychological processes involved in speech perception, is to systematically manipulate synthetic auditory and animated visual speech in an expanded factorial design. This paradigm is especially informative for defining the relationship between bimodal and unimodal conditions and for evaluating a model's specific predictions (see Massaro et al. [27]). Across a range of studies comparing specific mathematical predictions (see Chen and Massaro [28]; Massaro [7, 27, 29]), the FLMP has been more successful than other competitor models in accounting for the experimental data.

Previous tests of the FLMP did not include both a synthetic and a natural talker, and previous tests of intelligibility

Table 5: Sumby and Pollack's [1] metric (1) for both the test and reference and our metric for the relative visual contribution (3) for each participant in Experiment 2.

	Visual contribution of the lips across 5 noise levels (1)					Visual contribution of the face across 5 noise levels (1)					Relative visual contribution across 5 noise levels (3)				
Participants	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	0.37	0.34	0.37	0.41	0.49	0.37	0.50	0.57	0.65	0.56	1.00	0.69	0.65	0.62	0.88
2	0.37	0.17	0.34	0.62	0.48	0.52	0.27	0.37	0.72	0.41	0.71	0.64	0.91	0.86	1.15
3	0.09	0.09	0.11	0.05	0.17	0.13	0.16	0.30	−0.05	0.29	0.67	0.53	0.37	−1.00	0.58
4	0.37	0.34	0.24	0.59	0.46	0.34	0.46	0.41	0.49	0.41	1.10	0.75	0.60	1.20	1.13
5	0.19	0.13	0.26	0.31	−0.17	0.30	0.21	0.39	0.37	0.23	0.62	0.61	0.67	0.85	−0.73
6	0.46	0.52	0.36	0.35	0.56	0.50	0.67	0.76	0.60	0.75	0.92	0.78	0.47	0.59	0.75
7	0.12	0.34	0.46	0.44	0.07	0.42	0.46	0.46	0.33	0.54	0.28	0.75	1.00	1.31	0.13
8	0.12	0.20	0.20	0.44	0.24	0.19	0.37	0.44	0.44	0.35	0.61	0.56	0.46	1.00	0.68
Mean	0.26	0.27	0.29	0.40	0.29	0.35	0.39	0.46	0.44	0.44	0.74	0.66	0.64	0.68	0.57

Table 6: Sumby and Pollack's [1] metric (1) for both the test and reference and our metric for the relative visual contribution (3) for each participant in Experiment 3.

	Visual contribution of the lips across 5 noise levels (1)					Visual contribution of the face across 5 noise levels (1)					Relative visual contribution across 5 noise levels (3)				
Participants	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	0.48	0.46	0.56	0.81	0.31	0.68	0.63	0.64	0.81	0.69	0.71	0.73	0.87	1.00	0.46
2	0.46	0.57	0.36	0.37	0.32	0.42	0.62	0.54	0.57	0.50	1.11	0.93	0.66	0.65	0.64
3	0.54	0.37	0.38	0.34	0.45	0.50	0.51	0.58	0.66	0.61	1.08	0.73	0.67	0.51	0.73
4	0.59	0.53	0.71	0.70	1.00	0.63	0.72	0.79	0.76	0.77	0.94	0.73	0.90	0.92	1.30
5	0.66	0.63	0.65	0.69	0.82	0.73	0.63	0.74	0.79	0.94	0.90	1.00	0.87	0.87	0.88
6	0.44	0.48	0.73	0.68	0.60	0.53	0.61	0.63	0.63	0.60	0.83	0.79	1.16	1.08	1.00
7	0.65	0.58	0.70	0.54	0.73	0.69	0.71	0.74	0.46	0.63	0.93	0.82	0.94	1.18	1.15
8	0.61	0.66	0.65	0.87	0.60	0.69	0.58	0.74	0.87	0.81	0.88	1.13	0.87	1.00	0.73
9	0.51	0.56	0.58	0.45	0.72	0.58	0.56	0.79	0.85	0.61	0.87	1.00	0.74	0.52	1.17
10	0.65	0.56	0.53	0.78	0.88	0.65	0.72	0.47	0.84	0.80	1.00	0.78	1.12	0.93	1.09
11	0.75	0.60	0.58	0.85	0.92	0.71	0.80	0.79	0.77	1.00	1.06	0.75	0.74	1.11	0.92
12	0.49	0.71	0.72	0.37	0.73	0.68	0.66	0.67	0.71	0.80	0.73	1.07	1.08	0.51	0.91
13	0.51	0.44	0.54	0.67	0.57	0.51	0.44	0.63	0.67	0.84	1.00	1.00	0.86	1.00	0.68
14	0.66	0.63	0.74	0.78	0.88	0.66	0.75	0.65	0.90	0.81	1.00	0.84	1.14	0.87	1.08
15	0.40	0.68	0.59	0.47	0.54	0.60	0.64	0.59	0.69	0.73	0.66	1.05	1.00	0.69	0.73
16	0.71	0.80	0.66	0.58	0.78	0.66	0.80	0.92	0.87	0.78	1.07	1.00	0.72	0.67	1.00
17	0.40	0.68	0.59	0.47	0.54	0.60	0.64	0.59	0.69	0.73	0.66	1.05	1.00	0.69	0.73
18	0.48	0.44	0.64	0.70	0.32	0.64	0.65	0.72	0.76	0.75	0.75	0.67	0.90	0.92	0.42
19	0.66	0.76	0.79	0.88	0.83	0.75	0.81	0.69	0.73	0.83	0.88	0.94	1.15	1.20	1.00
20	0.63	0.82	0.73	0.77	0.66	0.46	0.61	0.63	0.77	0.80	1.37	1.35	1.16	1.00	0.82
Mean	0.56	0.60	0.62	0.64	0.66	0.62	0.65	0.68	0.74	0.75	0.92	0.92	0.93	0.87	0.87

as a function of noise level did not include a measure of the intelligibility of visible speech (see Massaro [7]). The present three experiments include these additional conditions, which allow us to use the FLMP parameter values to assess differences between test and reference conditions of the visual channel.

The FLMP was fit to the average results from each of the three experiments, pooled across participants and vowel, as a function of the test and reference conditions, the 5 noise levels, and the nine consonants. The fit of these 1377 independent data points required 567 free parameters. The FLMP did indeed give a good description of the results with RMSDs of 0.0277, 0.0377, and 0.0254 for the 3 respective fits.

Finally, when it provides a good description of the results, parameter values from the fit of the FLMP can be

Table 7: Parameter values from the fit of the FLMP, indicating the visual support for the nine consonants pooled across participants and vowel, as a function of the test and reference cases. The ratio gives the support from the test case divided by the support from the ideal case. The RMSDs were 0.0277, 0.0377, and 0.0254 for the 3 respective fits.

Experiment 1	/p/	/l/	/t/	/θ/	/s/	/ʃ/	/r/	/f/	/w/
Synthetic	0.999	0.400	0.944	0.832	0.916	0.987	0.492	0.996	0.606
Natural	0.999	0.902	0.949	0.999	0.836	0.999	0.336	0.998	0.997
Ratio	1	0.443	0.994	0.832	1.095	0.987	1.464	0.997	0.607
Experiment 2	/p/	/l/	/t/	/θ/	/s/	/ʃ/	/r/	/f/	/w/
Lips only	0.999	0.506	0.351	0.995	0.403	0.811	0.611	0.996	0.558
Synthetic	1.000	0.653	0.410	1.000	0.767	0.992	0.787	0.944	0.574
Ratio	0.999	0.775	0.856	0.995	0.525	0.818	0.776	1.055	0.972
Experiment 3	/p/	/l/	/t/	/θ/	/s/	/ʃ/	/r/	/f/	/w/
Lips only	1.000	0.944	0.832	0.997	0.793	0.997	0.344	0.952	0.940
Natural	1.000	0.942	0.973	1.000	0.849	0.985	0.316	0.845	0.978
Ratio	1.000	1.002	0.855	0.997	0.934	1.012	1.089	1.127	0.961

Table 8: Accuracy values for the nine consonants in the unimodal visual condition pooled across participants and vowel, as a function of the test and reference cases. The ratio gives the support from the test case divided by the support from the ideal case.

Experiment 1	/p/	/l/	/t/	/θ/	/s/	/ʃ/	/r/	/f/	/w/
Synthetic	0.967	0.133	0.400	0.367	0.367	0.700	0.400	1.000	0.367
Natural	1.000	0.633	0.367	0.667	0.300	0.933	0.133	0.900	0.967
Ratio	0.967	0.210	1.090	0.550	1.223	0.750	3.007	1.11	0.379
Experiment 2	/p/	/l/	/t/	/θ/	/s/	/ʃ/	/r/	/f/	/w/
Lips only	0.500	0.167	0.250	0.333	0.208	0.333	0.292	0.792	0.292
Synthetic	0.625	0.083	0.083	0.417	0.167	0.625	0.375	0.833	0.375
Ratio	0.800	2.012	3.012	0.798	1.245	0.533	0.779	0.950	0.779
Experiment 3	/p/	/l/	/t/	/θ/	/s/	/ʃ/	/r/	/f/	/w/
Lips only	0.783	0.450	0.433	0.767	0.250	0.650	0.250	0.850	0.867
Natural	0.833	0.517	0.417	0.833	0.300	0.683	0.233	0.950	0.917
Ratio	0.940	0.870	1.038	0.921	0.833	0.952	1.073	0.895	0.945

used to assess how well the test case does relative to the ideal case. These values are readily interpretable. Table 7 gives parameter values from the fit of the FLMP, indicating the visual support for the nine consonants pooled across participants and vowel, as a function of the reference case and test case in the first two rows of each experiment, respectively. The ratio in the third row of each experiment gives the support from the test case divided by the support from the reference case. This ratio provides an index of the quality of the synthetic face relative to the natural face. As can be seen in the parameter values in Table 7, the synthetic face Baldi in Experiment 1 provided fairly good visible speech relative to the reference. The average ratio of the visible speech parameter values was 0.935 so that one interpretation is that Baldi is about 93% as accurate as a real face. We should note that this relative difference in parameter values can produce a larger difference in overall performance because they are not linearly related. Thus, in this case, the relative difference in parameter values is much smaller than the relative difference in overall performance.

The individual ratios for the nine consonants also provide information about the quality of the synthetic speech for the individual segments. For example, /l/ and /w/ were most poorly articulated by the synthetic face relative to the natural face in Experiment 1. The segments $/p, t, s, ʃ, f/$, however, are basically equivalent for the synthetic and natural face. The segment /r/, on the other hand, is actually more intelligible with the synthetic than with the natural face.

The parameter values also inform the outcomes of Experiments 2 and 3. The face appears to add significantly to the lips for the synthetic face (Experiment 2) with an average ratio of 0.863. Only $/p, f, w/$ were about as informative with just the synthetic lips as the full synthetic face.

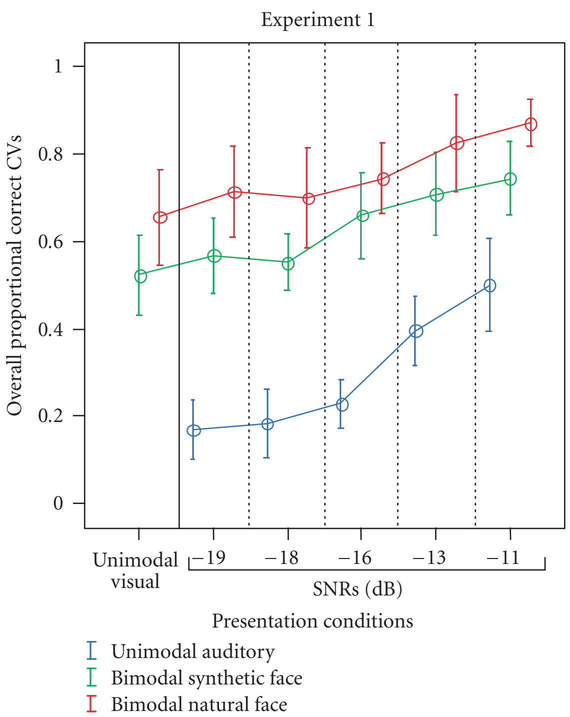


Figure 3: Overall proportional correct CVs across five noise levels (SNR in dB) in three conditions: unimodal auditory, bimodal AV-synthetic face, and bimodal AV-natural face. Error bars represent the mean +/ − 1 standard deviation. The figure includes also visual-only results.

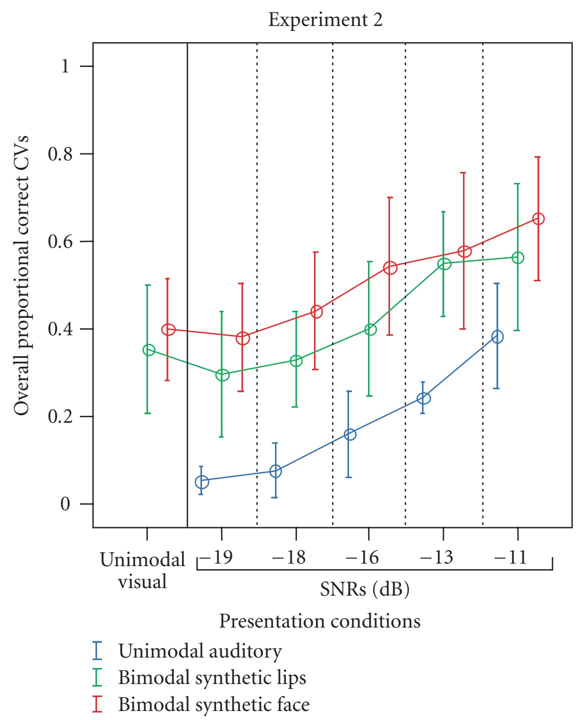


Figure 4: Overall proportional correct CVs across five noise levels (SNR in dB) in three conditions: unimodal auditory, bimodal AV-synthetic lips, and bimodal AV-synthetic face. Error bars represent the mean +/ − 1 standard deviation. The figure includes also visual-only results.

On the other hand, the natural lips gave roughly equivalent performance to the full natural face in Experiment 3, with a ratio of 0.997. Only /*t*/ was better with the full natural face than just the natural lips.

Table 8 gives the accuracy values for the nine consonants in the unimodal visual condition pooled across participants and vowel, as a function of the test and reference case. These results are mostly consistent with the parameter values shown in Table 7.

6. DISCUSSION

Providing a metric to evaluate the effectiveness of an animated agent in terms of the intelligibility of its visible speech is becoming important as there is an increasing number of applications using these agents. We derived a metric based on Sumby and Pollack's [1] original metric, which allows the comparison of an agent relative to a reference, and also propose a new metric based on the fuzzy logical model of perception (FLMP) to describe the benefit provided by a synthetic animated face relative to the benefit provided by a natural face. We tested the validity of these metrics in three experiments. The new metric presented reasonable results. The FLMP also gave a good description of the results.

Future studies should be aimed at implementing a wider range of noise levels to produce larger performance differences. As can be seen in Figures 3–5 and Tables 1–3, performance under the auditory-only condition improved only about 35% as noise level decreased. In the interim, we are somewhat uneasy about accepting our derived metric as an invariant measure because it is derived from measures that were found not to be invariant. Most generally, we believe that an invariant measure will be difficult to derive from just the bimodal conditions and the auditory-alone condition. A visual-only condition adds significant information to the test of any potential metric.

Since we measure the realism of our talking head through comparison with natural speech, it is important to realize that visual intelligibility varies even across natural talkers. Lesner [30] provides a valuable review of the importance of talker variability in speechreading accuracy. This variety across talkers is easy enough to notice in simple face-to-face conversations. Johnson et al. [31] found that different talkers articulate the same VCV utterance in considerably different ways. Kricos and Lesner [32] looked for large differences in visual intelligibility, and tested six different talkers who could be considered to represent the extremes in intelligibility because they were selected with this goal.

Observers were asked to speechread these six talkers, who spoke single syllables and complete sentences. Significant differences, but also some similarities, were found across talkers. Viseme groups were determined using a hierarchical clustering analysis. All talkers had the distinctive viseme category containing /*p*, *b*, *m*/. Four of the six talkers had the viseme

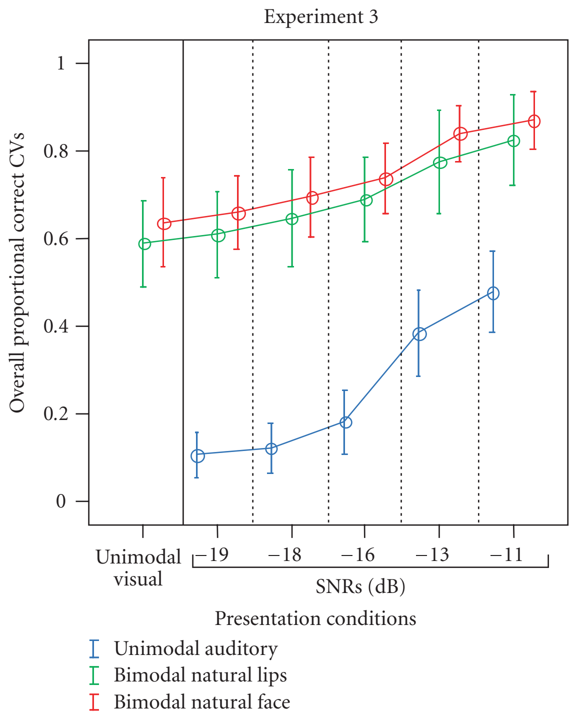


Figure 5: Overall proportional correct CVs across five noise levels (SNR in dB) in three conditions: unimodal auditory, bimodal AV-natural lips, and bimodal AV-natural face. Error bars represent the mean +/− 1 standard deviation. The figure includes also visual-only results.

/θ, ð/; for one other talker /r, w/ was grouped with /θ, ð/; and /θ, ð/ was not a distinctive viseme category for the sixth talker. Four of the six talkers had a unique viseme category /r, w/, whereas /r/ was grouped with /v, f/ for one of the talkers.

Even with talkers who were chosen to represent extreme differences in intelligibility, the actual speechreading scores varied only by about 17% on consonant recognition. Gesi et al. [33] studied four randomly chosen talkers, and found that speechreading accuracy varied across only a smaller 5% range. It was surprising that visual intelligibility differed so little across the four talkers even though two of the four talkers were nonnative speakers of English.

It may be the case that much of the variability inherent in visible speech is overcome by perceivers. Montgomery and Jackson [34] measured the videotaped images of four talkers speaking 15 vowels and diphthongs. They found significant differences across the four talkers, so that it was not possible to categorize the vowels simply based on a physical measure of overall lip opening. Given the good recognition performance of human perceivers, however, there appears to be sufficient information in the overall visible configuration to overcome the variability across talkers. As Lesner observes, perhaps visible speech perception involves a spatial normalization analogous to the normalization used by listeners to account for differences in frequency arising from vocal tract length. Thus, in summary, we believe that it remains to be demonstrated that talker variability is a significant barrier to the important contribution of visible speech to intelligibility.

The findings from our experiments contribute to the growing literature on visible and bimodal speech perception. Extant research has demonstrated that animated synthetic talkers have not yet achieved the accuracy of natural talkers (see Beskow et al. [11]; Massaro [7]; Ouni et al. [20]). Improvement in synthetic visible speech will be aided by research on determining which components of the face are important for visible speech perception (see Benoît et al. [2]; Preminger et al. [35]; Summerfield [4]). We found that the lips only were almost as effective as the full face for the natural face but much less so for the synthetic face. The explanation of this difference between the natural and synthetic face remains for future research. Another research, on the other hand, indicates that information from the face other than the mouth area can be used for visible speech perception (see Preminger et al. [35]). More generally, visible speech synthesis offers a potentially valuable technique for systematically varying the components of the face to determine the important cues for speechreading. This technique along with improved metrics for quantifying the contribution of visible speech should advance our understanding of speech perception.

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