CHARACTERIZATION OF VISUAL PROPERTIES OF SPATIAL FREQUENCY AND SPEED IN AMERICAN SIGN LANGUAGE

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Abstract

Careful measurements of the dynamics of speech production have provided important insights into phonetic properties of spoken languages. By contrast, analytic quantification of the visual properties of signed languages remains largely unexplored. The purpose of this study was to characterize the spatial and temporal visual properties of American Sign Language (ASL). Novel measurement techniques were used to analyze the *spatial frequency* of signs and the *speed* of the hands as they move through space. In Study 1, the amount of energy (or "contrast") as a function of spatial frequency was determined for various sign categories by applying a Fourier transform to static photographs of two ASL signers. In order to determine whether signing produces unique spatial frequency information, amplitude spectra of a person signing were compared to those of a "neutral" image of a person at rest (not signing). The results of this study reveal only small differences in the amplitude spectra of neutral versus signing images across various sign forms examined. In Study 2, three ASL signers wore small ultrasonic devices on the back of their hands during sign production, yielding measurements of hand position in 3-dimensional space over time. From these data, we estimated the speed of signs. Here, we found significant differences in speed between grammatically inflected signs and signs with no inflection. Overall, the spatial frequency content and speeds of signs were found to fall within a selective range, suggesting that exposure to signs is a specific and unique visual experience, which might alter visual perceptual abilities in signers, even for non-language stimuli.

1. Introduction

Recent experimental studies with native users of signed languages have suggested that daily experience with a visual sign language may improve or alter visual perception for non-language stimuli. For example, compared to hearing people who have no exposure to sign language, deaf and hearing native signers have been shown to possess enhanced or altered perceptual abilities along several visual dimensions, such as motion processing (Bosworth & Dobkins 1999; Neville & Lawson 1987), mental rotation (Emmorey, Kosslyn & Bellugi 1993), and processing of facial features (McCullough & Emmorey 1997).

These alterations in perceptual abilities in signers are thought to be due to their lifelong experience with a visual, signed language, since motion processing, mental rotation and facial processing are believed to be required for sign language comprehension.

Aside from enhancing visual processing, experience with a visual signed language has also been found to alter how visual stimuli are perceptually *categorized*. For example, Poizner (1983) found that signers of American Sign Language (ASL) perceive moving patterns in such a way that reflects various phonological categories in ASL. By placing light emitting diodes (LEDs) on the hands and body of a signer and recording only visible moving points of light during signing, Poizner was able to reduce information of signs to only the movement and relative positions of the LEDs. Deaf signers and hearing nonsigners performed a perceptual judgement task in which they chose two out of three LED movement patterns that appeared most similar to each other. By applying a multidimensional scaling technique to the similarity judgements, Poizner found that signers' judgements revealed categories of perceived 'similar' movement that differed from those of hearing nonsigners. Although this task did not require any language processing whatsoever, the signers' judgements were nonetheless carved along characteristics of various types of lexical and inflectional movement, while the nonsigners' were not. Poizner inferred that these perceptual categories were based upon features of *linguistic salience* for ASL signers and *perceptual salience* for nonsigners, supporting the notion that language experience can alter perceptual processing. Although Poizner's results suggest that language experience can modify categorization of perceptual events, it was not clear whether his subjects relied solely on the motion percept since the LED movement patterns may not have eliminated all access to linguistic cues. Moreover, the physical properties of the LED movement patterns and whether they varied across lexical or inflectional categories in a random or specific way were not quantitatively described or controlled in Poizner's study. As a consequence, while it is apparent that subjects' perceptual judgements reflected basic language categories of ASL, it is not clear what aspects of the movement patterns mediated these perceptual categories.

In another study by McCullough, Brentari & Emmorey (2000) investigating categorical perception, the visual properties of the stimuli were controlled more directly. In this study, the investigators asked whether perception of hand configuration and location of articulation were influenced by language experience. They found that ASL signers revealed better discrimination compared to hearing nonsigners of two hand configuration stimuli that belonged to different "phonemic" categories (i.e., the closed "A" fist handshape vs. the flat "B" palm upright handshape) and not of two stimuli within one phonemic category (i.e., two variants of the "A" fist handshape). Evidence of categorical perception was not found for place of articulation (specifically, forehead vs. chin). This result shows that some visual stimuli can be perceived in ways that do not reflect their actual physical properties, but rather reflect phonemic distinctions within the signed language.

The above-described reports of altered visual processing and categorical perception in signers suggest that sign language experience can modify perception of non-linguistic visual stimuli. Experience with a visual language may exert its effects at relatively low-levels of visual processing in signers. That is, it is possible that continual visual stimulation (which necessarily occurs from conversing in sign language) produces altered sensitivity for those aspects of vision required for sign language processing. Specifically, if stimulus-specific visual improvement occurs as a result of experience with a visual language, then perceptual changes should be observed *within* the range of visual properties inherent in sign language and not outside this range. To investigate this possibility, however, one must first characterize the *physical* properties of sign language signals, whether they are continuous across phonetic boundaries and whether they fall within narrow ranges that separate the sign language signal from other naturally occurring visual stimuli.

To this end, the present study analyzed two properties of signs in American Sign Language, *spatial frequency* and *speed*, and determined whether they vary across phonological categories in a random or specific way. To quantify these two visual properties of signs, we analyzed the spatial frequency content within static photographic images of signs using Fourier analyses in Study 1 and the speed of the hands as they moved through signing space in Study 2. The results from the current study can be, and are being, used to design studies of visual perception in deaf people (e.g., Bosworth & Dobkins 1999; Finney & Dobkins 2001).

2. Study 1: spatial frequency

One way to describe the spatial properties of patterns and scenes is with a Fourier analysis, which quantifies the amount (or "amplitude"[1]) of luminance contrast as a function of spatial frequency contained in the image. Spatial frequency is defined as the number of cycles of light and dark variations across space. Low spatial frequencies (e.g., 2 cycles per degree of visual angle) make up the large, coarse portions of an object (like the global shape of a tree), whereas high spatial frequencies (e.g., 20 cycles per degree) make up the small, detailed portions of an object (like the individual leaves on the tree). When an image of a scene becomes blurry, only low spatial frequencies remain, and the fine detail that is lost is the high spatial frequencies. The plot of amplitude against spatial frequency is the image's "amplitude spectrum". The term "energy", the square of the amplitude, is often used to refer to an image's spatial frequency composition.

In several previous studies, researchers have investigated which spatial frequencies are important for the visual perception of specific objects, such as letters (e.g., Parish & Sperling 1991) and faces (e.g., Ginsburg 1978), by measuring the effects of filtering out certain ranges of spatial frequencies on object recognition. In general, 2 to 6 cycles per letter have been found to be crucial for letter identification (Gold, Bennett & Sekular 1999; Legge, Pelli, Rubin & Schleske 1985; Parish & Sperling 1991; Peterzell, Harvey & Hardyck 1989; Solomon & Pelli 1994). Results have been somewhat mixed for face stimuli, with some studies reporting low (1 cycle per face, Rubin & Siegel 1984), and others reporting medium (approximately 6 cycles per face, Bachmann 1991; Costen, Parker, & Craw 1994; Gold, et al 1999) or high (25 cycles per face, Hayes, Morrone & Burr 1986) spatial frequencies as being critical for face identification. Most relevant to the present study, Riedl & Sperling (1988) performed a similar analysis with ASL signs, and found that sign recognition was reduced drastically when high spatial frequencies were filtered

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[1] Fourier analysis defines the image as a linear combination of sine wave gratings of various frequencies. "Amplitude" refers to the amplitude of the sine wave at a given spatial frequency that makes up the image.

from the image. Thus, such findings suggest that sign language comprehension relies mainly on higher spatial frequency information present in the image. In accordance with these results, other studies have shown that ASL sign comprehension is impaired when high spatial frequency information is degraded by an impeding screen placed in front of the signer (Naeve, Siegel & Clay 1992) or by masking the video image of a signer with high spatial frequency noise (Sperling 1980). Thus, although the image of a signer contains many (low to high) spatial frequencies, the results from these previous studies suggest that only the high spatial frequencies are likely to be important for adequate perception and comprehension of signs.

In the present study, we obtained amplitude spectra (amplitude of contrast as a function of spatial frequency) from a sample of signs in American Sign Language. In particular, we asked whether sign images contain unique spatial frequency information as compared to that of a "neutral" image of a nonsigning person. Two comparisons were conducted between sign images with the following phonological forms: 1) signs with one hand vs. signs with two hands and 2) signs with and without handshape and location changes. These particular features were compared because they are common in many signed languages, and because they contain salient visual differences in the positions of the hands and arms, which we expect might produce differences in spatial frequency content.

2.1 Methods

Two fluent signers of ASL (RB and DH) participated in this study. Both were female and learned ASL by the age of 10 years and had been signing for 18 years.

Forty-three signs were selected for sign production. We attempted to select signs that varied in phonological structure in order to obtain a diverse sample, and so that we could make comparisons between different phonological forms. (See Appendix for a list of the signs used.) In addition, we obtained images of each signer in a "neutral" nonsigning position (i.e., hands resting at the signer's sides). Sign production data were obtained from each signer separately.

The signer, who wore a white bodysuit and pants, stood against a white background (see Figure 1). The purpose of the white clothing was to minimize edges in the image created by the contrast of the signer's torso with the background. Both participants wore identical white clothing in order to minimize differences between signers.[2] All photographs were taken at a distance of 63.5 inches. Two photographs were obtained during the production of each sign (see Figure 1 for examples). For signs with a motion path (such as GIVE, IMPROVE, SMART), photographs were taken at initial and terminal points of the motion path. For signs with handshape changes (such as ASK, CAT, FIND), images were obtained of initial and terminal handshapes (for example, the sign ASK starts with the "S" fist handshape and ends with the "G" extended-index-finger handshape). For signs with

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[2] Edges and lines in these photographs (resulting from creases in the clothing and the contrast of the signer's torso against the background) will produce noise in the Fourier spectrum, as will variations in body and facial features. However, since we are investigating the *difference* in energy across spatial frequency of signing vs. not signing *within* a single person, this noise is expected to be largely factored out.

circular motion (such as BICYCLE, ENJOY, GESTURE), images at the start of the circular motion and at the half-way point of the motion cycle were obtained. Finally, some signs had a single contact point, in which two photographs were taken of the same point (for example, CANADA, HAVE, KNOW). In order to obtain photographs of these different points in the sign, the signer was instructed to temporarily freeze the motion of sign to reduce image blur. A total of 112 photographs were included in our analyses (subject RB: 58 photographs, subject DH: 54 photographs). (Note that some photographs had to be eliminated due to poor photograph development.) Each image was scanned using an Epson Scanner set at 600 dpi. Images were all set to the same window size. The resulting images were 1800 x 2400 pixels, with a head width of 400 pixels, measured ear to ear.

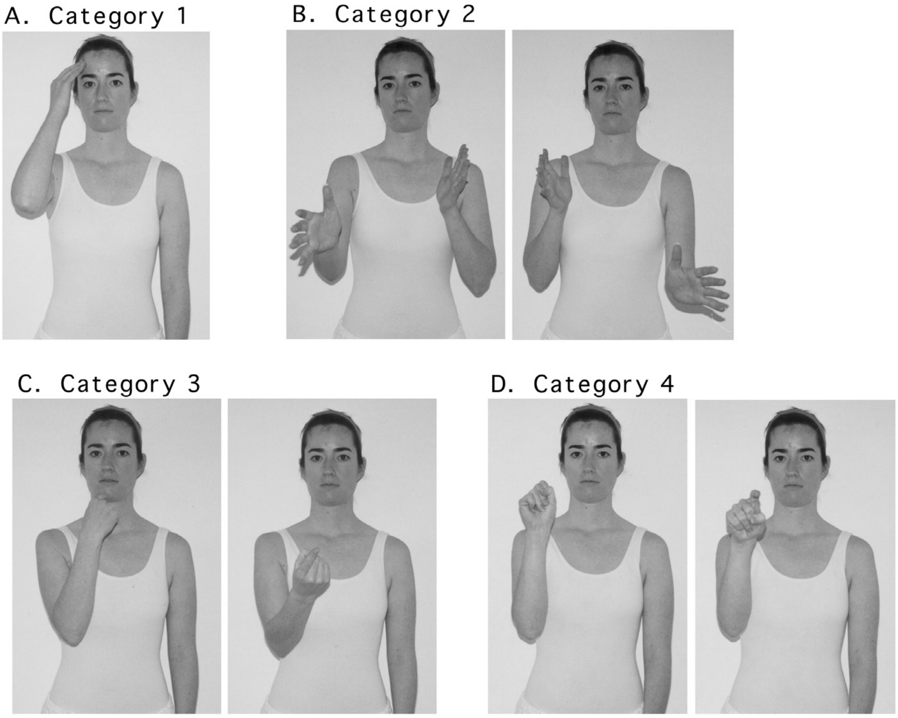

Figure 1: Example photographs are presented for each category of handshape and location change: a) Category 1 - KNOW; b) Category 2 - GESTURE; c) Category 3 - TELL; d) Category 4 – ASK. In category 1, only one figure is shown because there was minimal or no displacement of the hands between the first and second images of these signs. Fourier analyses were performed on photographs of signs such as these, in order to determine the spatial frequencies inherent in signs.

Amplitude spectra were calculated for each image using MATLAB (by MathWorks). These were computed using a two-dimensional (2-D) discrete fast Fourier transform function. The two-dimensional output (amplitude as a function of spatial frequency and orientation) was reduced to 1-D by collapsing across orientation. Spatial frequency was computed in terms of cycles per image, which was then converted to cycles per degree (cyc/deg) by assuming a viewing distance of five feet. Amplitudes (defined as the square root of energy) at each spatial frequency, ranging from 0.02 to 30 cyc/deg, at 0.02 intervals, were calculated, yielding an amplitude spectrum for each image. In order to simplify our analyses, spatial frequency was collapsed into six groups with the following midpoints: 0.5, 1.6, 3.0, 6.0, 13.5, and 23.8 cyc/deg.[3]

In order to determine whether signs contain unique spatial frequency information that differs from that inherent in a neutral image of a signer not signing, we calculated Sign:Neutral ratios by dividing the amplitude of a sign image by the amplitude of a neutral image. Sign:Neutral ratios equal to 1.0 indicate that the sign image has the same amount of energy as the neutral image. Ratios greater than 1.0 indicate that the sign image has more energy than the neutral image. Two types of neutral images were used in calculating ratios:

1. $\text{Neutral}_{\text{arms resting}}$ image: the signer's arms resting at side;
2. $\text{Neutral}_{\text{arms deleted}}$ image: the "signing articulators" (fingers to shoulders) were deleted from the $\text{Neutral}_{\text{arms resting}}$ image of the signer and replaced with the background luminance.

The $\text{Sign:Neutral}_{\text{arms resting}}$ ratio reflects the difference in amplitude between signing arms and resting arms, and can thus be considered the "*signing energy*". The $\text{Sign:Neutral}_{\text{arms deleted}}$ ratio reflects the overall energy inherent in the fingers, hands, and arms of a signer, and can thus be considered the "*articulator energy"*. Ratios were calculated for each spatial frequency interval, image, and signer.

Using these ratios, we investigated two questions: 1) Do signing energy and articulator energy of one-handed signs differ significantly from two-handed signs? 2) Do signing and articulator energy vary as a function of handshape and location change?

Analysis 1: one-hand vs. two-hand signs. For this analysis, a total of 35 images of one-hand signs and 36 images of two-hand signs from both subjects were analyzed.[4] Sign:Neutral ratios were treated as a dependant variable in an Analysis of Variance (ANOVA) with one- vs. two-hand category as a between-subjects factor and spatial frequency as a repeated measures factor (6 groups between 0.5 to 24 cyc/deg).[5]

Analysis 2: signs with vs. without hand change. In a second analysis on these same ratios, we compared 68 images of signs with various phonological forms based upon changes in handshape and location between the first and second photographed image of each sign. The two images for each sign were averaged within the sign's "hand change" category. Four hand change categories of signs were compared (see Figure 1 for examples):

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[3] The six spatial frequency groups have the following ranges: 0.14-0.92, 0.94-2.33, 2.35-3.73, 3.75-8.40, 8.42-18.68, 18.70-28.96 cyc/deg. In these studies, we assumed a viewing distance of five feet, which we noticed to be a typical conversing distance between signers. At this viewing distance, one inch is approximately equivalent to one degree of visual angle.

[4] These images are of the 40 signs listed in the Appendix. There were small differences in which signs were used from each subject, as some images had to be removed due to poor development.

[5] For all univariate tests, Greenhouse-Geisser corrections were applied to adjust for possible violations of the sphericity assumption. The original degrees of freedom are reported with resulting adjusted probability levels of the test outcome.

1. Single contact to the signer's body and no handshape change (e.g. KNOW);
2. Circular motion with no change in handshape (e.g., GESTURE);
3. Change in location with no change in handshape (e.g., TELL);
4. Change in location and handshape (e.g., ASK).

In category 1, the first and second images were very similar since there was minimal displacement of the hands in these signs (hence, in Figure 1, only one image is shown). In category 2, images were obtained at the initiation and the mid-point of a complete movement cycle for the right hand. In category 3, images were obtained at the beginning and ending of the motion path (e.g., $\text{IMPROVE}_{\text{1st contact point}}$ and $\text{IMPROVE}_{\text{2nd contact point}}$). In category 4, images were obtained for initial and terminal handshapes (e.g., $\text{ASK}_{\text{S handshape}}$ and $\text{ASK}_{\text{G handshape}}$).[6]

Sign:Neutral ratios were treated as a dependant variable in an ANOVA with a between-subjects factor of hand change (four categories: single contact, circular motion, change in location, and change in location and handshape) and spatial frequency as a repeated measures factor (6 groups between 0.5 to 24 cyc/deg). Note that both analysis 1 and analysis 2 treated individual sign images as subjects, averaging over signers. In addition, both analyses were conducted separately for $\text{Sign:Neutral}_{\text{arms resting}}$ ratios and $\text{Sign:Neutral}_{\text{arms deleted}}$ ratios.

2.2 Study 1 results and discussion

Overall signing and articulator energy. In Figure 2, $\text{Sign:Neutral}_{\text{arms resting}}$ ratios (i.e., the "signing energy") and $\text{Sign:Neutral}_{\text{arms deleted}}$ ratios (i.e., "articulator energy") are plotted against spatial frequency, separately for one- vs. two-hand category and signers, DH and RB. Across spatial frequencies and the two signers, the mean signing energy was 0.95 (open circles), very near 1.0, indicating that images of a person signing do not produce more energy than a neutral image of the same person not signing. Articulator energy (solid squares) was large at all spatial frequencies, primarily at high spatial frequencies (>10 cyc/deg), indicating that the articulators contained predominantly high spatial frequency information, relative to the body. As can be seen in Figure 2, the overall mean articulator energy collapsed across DH and RB was 1.18 between 0.5 and 6.1 cyc/deg, indicating that the articulators had 1.18 times more amplitude then the rest of the image of a signer at these spatial frequencies. Between 13.6 and 23.8 cyc/deg, the mean ratio was 1.38. This main effect of spatial frequency on articulator energy was significant ($F(5, 345) = 19.7$; $p < .0001$). Note, however, that since the signing energy was insignificant, this large proportion of articulator energy did not depend upon whether the articulators were signing or resting.

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[6] Although the same signs are used in the one- vs. two-hand analysis (Figure 2) and the hand change analysis (Figure 3), the total number of items differs between these two analyses. Specifically, there are fewer items in the hand change analysis, as some signs did not fit cleanly into one of the four categories.

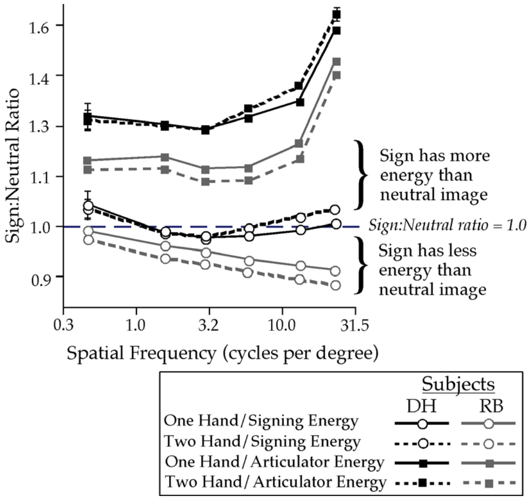

Figure 2: Mean Sign:Neutral amplitude ratios, averaged across sign images separately for the two neutral conditions (signing energy: open circles, and articulator energy: solid squares), are plotted as a function of spatial frequency. One-hand (solid lines) vs. two-hand (dotted lines) sign images are plotted for each signer, DH (black lines) and RB (gray lines). Error bars denote standard errors (s.e.) of the mean.

One- vs. two-hand signs. The results presented in Figure 2 also demonstrate that the amount of signing energy and articulator energy was similar for one-hand (solid lines) and two-hand signs (dotted lines). The effect of one- vs. two-hand category was not significant for either signing energy ($F(1, 69) < 1$) or articulator energy ($F(1, 69) < 1$). No significant interaction was observed between hand category and spatial frequency for signing energy ($F(5, 345) = 2.4$; $p > .05$) or for articulator energy ($F(5, 345) = 1.8$; $p > .05$). From the pattern of sign energy in the graphs, RB shows no interaction between hand category and spatial frequency. On the other hand, for subject DH, two-hand signs produced greater signing energy than the neutral image at 13.5 and 23.8 cyc/deg, while no signing energy above the neutral image was observed for one-hand signs.

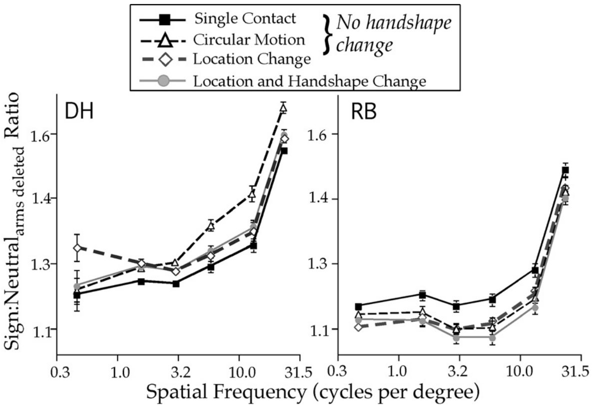

Figure 3: Mean articulator energy (Sign:Neutralarms deleted amplitude ratios; ± s.e.), averaged across individual sign images, are plotted separately for DH (left panel) and RB (right panel). The different symbols/line categories represent four "hand change" sign categories: 1) Single contact (e.g., KNOW); 2) Circular motion (e.g., GESTURE); 3) Change in location (e.g., TELL); 4) Change in handshape and location (e.g., ASK).

Handshape and location change. In Figure 3, averaged Sign:Neutral$_{\text{arms deleted}}$ ratios are presented separately for each hand change category and signer. (Sign:Neutral$_{\text{arms resting}}$ ratios are not presented since these values were equivalent to 1.0, as seen in Figure 2.) The results of these analyses demonstrated no differences between the four hand change categories, with respect to either signing energy ($F(3,64) = 1.9$; $p > .05$) or articulator energy ($F(3,64) = 2.0$; $p > .05$). Signs with change in location and handshape (category 4, filled circles) did not produce more overall energy in the articulators than the other hand change categories that contain location change or no change. However, a significant interaction was found between hand change category and spatial frequency ($F(15,320) = 2.6$; $p < .01$), suggesting that the pattern or slope of articulator energy across spatial frequencies differed between hand change categories. However, this pattern of energy across the sign categories was not consistent for the two signers. That is, for signer RB, signs with no change in handshape or location (category 1, filled squares) produced the most energy, while this category produced the least energy for signer DH. The variability between the two signers in the pattern of energy for the four sign categories points to a lack of relationship between sign category based on hand change and spatial frequency.

These results indicate that the articulators (fingers, hands, and arms) have a large amount of spectral energy, primarily at the high range of spatial frequencies, between 10 to 30 cyc/deg. The absence of significant main effects of one- vs. two-hand category or hand change category upon articulator energy indicates that the shape of the amplitude spectra remains consistent across the different sign phonology types compared in this study. In addition, the shape of the spectra is consistent across signers. These results suggest that the spatial frequency make-up of the articulators is relatively stable across arm and hand positions of signers. Although the absolute spatial frequency content alone does not distinguish between signs, the interaction of spatial frequency and *orientation* of the hands and arms (which was collapsed in this study) may be a critical factor in differentiating signs. In addition, it should be noted that in this experiment, spectral energies were generated from static images that represent only two points in the signing stream. These initial studies do not assess whether there is a differentiation of spectral energy as the signing hands move over time, an issue that awaits further study.

3. Study 2: measurements of speed in moving signs

Motion is a critical component of sign language perception. Often slight changes in movement, while all other parameters such as handshape and location are held constant, can change meaning (for example, the signs, SERIOUS and MISS in ASL). In fact, Emmorey & Corina (1990) have shown that identification of a sign is contingent upon identification of the sign's movement. As reviewed in the introduction, Poizner (1983) observed that signers perceive meaningless motion patterns in ways that are shaped by the morphological and lexical status of these motion patterns. Moreover, modulations of movement play a significant role in linguistic contrasts at all levels of structure in ASL. For example, differences in movement trajectory signal contrastive events at morphological and syntactic levels. At the suprasegmental level, differences in signing speed have been shown to impart prominence and stress distinctions in ASL (Wilbur 1999). In sum, signers must attend to the trajectory and speed of the moving hands in order to extract linguistic information.

This reliance on motion trajectories in signs led us to hypothesize that processing of non-language motion stimuli may be enhanced or altered by sign language experience. Evidence for such effects has been reported by Neville & Lawson (1987) and Bosworth & Dobkins (1999). These researchers investigated the ability to discriminate direction of moving stimuli in deaf signers, hearing signers, and hearing nonsigners.They found that both deaf and hearing signers possess a right visual field (i.e., left hemisphere) advantage for this task, while hearing nonsigners exhibited no visual field asymmetry or a slight opposite asymmetry (i.e., a left visual field/right hemisphere advantage). Since the left hemisphere is believed to be dominant for sign language processing (Corina, Vaid, & Bellugi 1992; Emmorey & Corina 1993; Poizner, Battison, & Lane 1979), the lateralization of motion processing in deaf and hearing signers may be due to a "language capture" effect, wherein motion processing gets usurped by the left, language-dominant hemisphere of the brain. If exposure to motion in sign language influences perceptual processes in this manner, such effects may be specific for the range of motion speeds inherent within the language. That is, signers may exhibit sensitivity for the range of speeds observed within sign language, but not outside this range.

In order to obtain the range of speeds inherent in ASL, we measured minimum, median, and maximum speeds for a variety of signs. In addition we investigated whether the speed of signing differs across various phonological forms.

2.1 Methods

Hand motion during sign production was measured in three fluent ASL signers, two of whom were also in Study 1. The third signer, MV, was a second generation native signer. Signers produced 40 pre-selected signs (see appendix for a list of signs). Each sign was embedded in a carrier phrase, "SIGN X EASY", where X represents the sign of interest (i.e., the “target” sign). The purpose of employing a carrier phrase was to embed signs within a natural sentence context. For each phrase, the signer began and ended with her hands resting at her sides. Each phrase was repeated three times, yielding 120 total items.

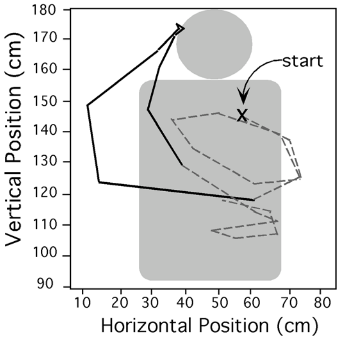

Figure 4: Example two-dimensional motion trajectory of the right dominant hand for the ASL phrase, SIGN KNOW EASY (English gloss: “To sign the word ‘know’ is easy.”) obtained from signer RB. In this example the target is KNOW, delineated by the solid line, with the dashed line representing the carrier phrase. The “X” marks the start of the phrase. The line indicates the change in x and y position of the hand (in centimeters) as a function of time. (Note that the “z” position could not be shown here.)

Measurements of hand motion were obtained using an InterSense 3-Dimensional motion measurement system at the Virtual Reality Laboratory at University of California, Irvine. Signers wore flexible, fingerless gloves with small ultrasonic position trackers placed firmly on the back of each hand. These devices emitted ultrasonic signals at a rate of 60 Hertz, which were recorded by a receiver placed on the ceiling above the signer. These signals provided the x (horizontal), y (vertical), and z (depth) position of the hands every 16.7 milliseconds, as the subject signed (see Figure 4).

For each signed phrase, the portion of the movement trajectory associated with the target sign was excised from the carrier sentence as follows. Because the non-target signs (SIGN and EASY) of the carrier phrase had movement patterns that were fairly consistent across signed phrases, we constructed an algorithm (using S+ by Mathsoft) that automatically identified movement at the start and end of each phrase that was associated with those consistent patterns. Specifically, the beginning of the movement trajectory was characterized by a large initial change in the vertical position of the hands, resulting from both hands rising from the resting position (i.e., signer’s hands at sides), followed by cyclic repetition in the vertical dimension, resulting from generating SIGN. Likewise, the end of the movement trajectory was characterized by two rapid changes in vertical position, resulting from generating EASY, followed by a large change in vertical position, resulting from the hands returning to their resting state (see Figure 4). The algorithm deleted these motion patterns from each phrase, based upon x, y, z position data over time, leaving only the target sign for further analysis. As an additional check, a trained signer (the first author) examined each case to ensure that the non-target portions of the phrase had been properly excised. In the majority of cases, no corrections were necessary. However, in some rare cases, the program excised too much or too little of the target sign, which was remedied by demarcating the target by hand.

Once the target sign was extracted, two-dimensional (2-D) and three-dimensional (3-D) speed of the hands was determined from the change in position (in centimeters) over time for each target. Two-dimensional speed was calculated from the speed of motion in the x dimension (horizontal speed, i.e., how fast the hand moves leftward or rightward) and the y dimension (vertical speed, i.e., how fast the hand moves upward or downward). Three-dimensional speed was calculated based upon the speed of motion in the x and y dimensions, as well as the z dimension (looming speed of the hand, i.e., how fast the hand moves towards or away from the signer). These values were calculated between consecutive position samples obtained every 16.7 msec, from beginning to end of the excised sign. These speed values were converted from centimeters per second to degrees per second (deg/sec), based on a viewer's point of view five feet away from the signer. Cumulative frequency distributions of speed values were calculated for each sign target. Based on these distributions, the minimum (0% quantile), median (50%), and maximum (100%) speed for each sign was obtained. Since each sign was repeated three times, these quantile values were averaged across the three trials per sign. Note that although sensors were placed on both hands, only data from the dominant, right hand are analyzed here.

In order to determine whether signing speed varied as a function of sign type, the quantile data were averaged across the three signers and grouped into categories based upon changes in hand configuration or location.[7] These categories were:

1. Repetition, with no change in handshape or location (e.g., DOCTOR, CANADA);
2. Circular motion, with no handshape change (e.g., BICYCLE, GESTURE);
3. Single contact, with no change in handshape or location (e.g., HAVE, KNOW);
4. Handshape and location change (e.g., SEND, ASK);
5. Location change, with no handshape change (e.g., SMART, IMPROVE);
6. Inflected motion (e.g., GIVE and TELL with temporal aspect inflection).

A 6 (between factor: sign categories) by 3 (repeated factor: 0%, 50%, 100% quantile) ANOVA was conducted on these quantile speeds for each sign, separately for 2-D and 3-D speeds.

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[7] Note these sign categories are different from those used in Study 1. This is because in Study 2, categories were based on type of motion trajectory or path within signs, whereas in Study 1, categories were based on initial and terminal *static* images of each sign, with no regard for motion trajectory.

3.2 Study 2 results and discussion

Two- and three-dimensional speeds at each 0%, 50%, and 100% quantile (minimum, median, and maximum speed) averaged across signers for each sign category are presented in Figure 5. Mean 2-D speed across categories was 16.7 deg/sec (SD = 4.7), while the minimum was 3.6 (SD = 1.3) and maximum was 41.6 (SD = 17.8). As expected, 3-D speed was faster than 2-D speed, with a median value of 23.2 deg/sec (SD = 5.2), minimum of 6.8 (SD = 2.1) and maximum of 53.1 (SD = 17.2).

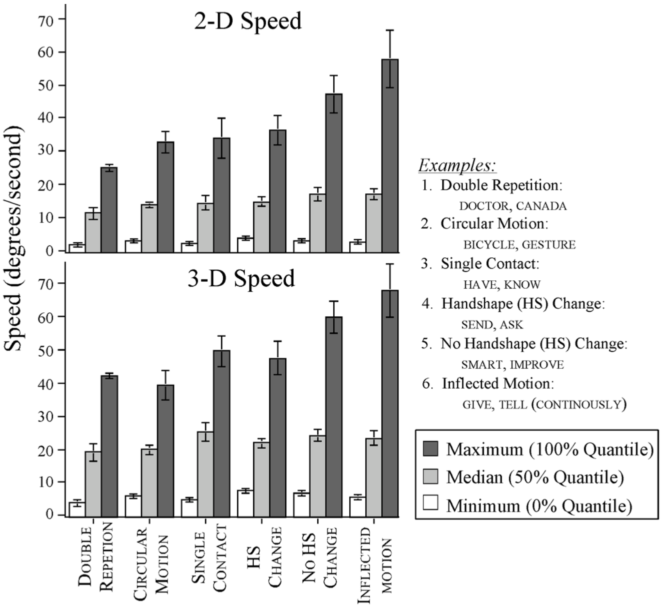

Figure 5: Mean 2- and 3-dimensional speed (± s.e.) plotted for each sign category, averaged across the three signers. Data are shown for the minimum values (0% quantile), median values (50% quantile), and maximum values (100% quantile). Upper graph: Mean 2-D speed was 16.7 degrees per second (SD = 5). Lower graph: Mean 3-D speed was slightly faster, at 23.2 degrees per second (SD = 5).

A small but significant main effect of sign category was found, for both 2-D speeds (F(5,34) = 3.1; p = 0.02) and 3-D speeds (F(5,34) = 2.9; p = 0.03). Post hoc comparisons between sign categories were conducted, with a Bonferroni correction applied to maintain the family-wise critical alpha at p = 0.05. Only two comparisons were significant. For the fastest (100% quantile) 2-D speeds, signs with inflected movements were significantly faster than signs with repetition movement (category 6 faster than category 1, p = 0.003). For the fastest (100% quantile) 3-D speeds, signs with inflected movements were faster than signs with circular movement (category 6 faster than category 2, p = 0.003).

The results of these analyses demonstrate that the median 2-D and 3-D speeds of signs fall within a specific range, between 12 and 28 deg/sec. For minimal speeds, the range is

2 to 9 deg/sec. Note that these minimal speed values include "pauses" or decelerations in movement, as when a motion path has been completed or when contact is made, before changing or reversing motion direction. For the maximum 2-D and 3-D speeds, the range is 24 to 70 deg/sec. In sum, while the minimum and median speeds do not vary across the sample of signs in this study (see Figure 5), the *fastest* 2-D and 3-D speeds vary substantially across sign categories. Preliminary results from this study indicate that the fastest maximal speeds were found in signs with inflected motion (e.g., TELL-continuously), and that these speeds were significantly faster than the maximal speeds seen in signs with repetitive (e.g., DOCTOR) or circular motion (e.g., GESTURE). This effect is perhaps due to the fact that inflected signs require the motion to occur over a *larger* area in signing space. If the duration of all signs is roughly constant, as has previously been suggested (Bellugi & Fischer 1972; Grosjean 1980), this would necessarily result in faster motion for signs that traverse greater distances. Although speculative, the functional utility of preserving the duration of sign utterances may be to maintain a constant pace and alleviate processing demand.

4. General discussion

The results of these studies provide the range of spatial frequencies and speeds inherent in American Sign Language. In our spatial frequency analysis, we found that the amplitudes of different spatial frequencies did not vary between signing and nonsigning images (i.e., mean Sign:Neutral$_{\text{arms resting}}$ ratio = 1.0), indicating that no energy exists in signs over and beyond that inherent in arms at rest. However, in relation to the rest of the body, the articulators (fingers to shoulders) were found to contain more energy at higher spatial frequencies (i.e., between 10 to 30 cycles per degree at a viewing distance of five feet). This range of spatial frequencies was not dependent on whether signs required one hand or two hands (Figure 2) or on the change in hand configuration or location in signs (Figure 3). Although the constancy of spatial frequency information across sign categories suggests that this aspect of the visual image is unlikely to aid in discriminating between different signs, the overall predominance of high spatial frequencies in signs may nonetheless have consequences for visual perception in deaf people. That is, because deaf people attend to the articulators of a signer, they receive constant exposure to a narrow range of spatial frequencies. As a consequence of this exposure, signers' sensitivity to non-linguistic spatial stimuli may be altered compared to nonsigners. Specifically, whereas hearing people exhibit the greatest sensitivity to spatial frequencies in the range of 4 to 8 cycles per degree (with a sensitivity cut-off at approximately 40 cycles per degree, Kelly 1979), deaf people may exhibit a shifted sensitivity peak towards the higher spatial frequencies due to the relative importance of higher frequencies in the processing of the articulators used in sign language.

In our motion analyses, we found a relatively selective range of speeds across signs. Interestingly, the median and maximal 2-D speeds obtained in our study are consistent with those of Fischer, Delhorne, & Reed (1999) who studied the effect of presentation rate of signed words and sentences upon subjects' identification accuracy of signs. They found that accuracy became significantly worse when presentation rate was increased by 2.5 times the normal rate. This value thus reflects the "maximal" limit for accurate identification. Assuming that their normal presentation rate was equivalent to our average hand motion speed for 2-D motion (since they presented sign stimuli on video), their value of 2.5-fold translates into a maximal speed of 41.75 deg/sec. This value is strikingly similar to the average maximum speed we observed, 41.6 deg/sec. This marked concordance between their study and ours suggests that the range of speeds inherent in sign language (3.6 to 41.6 deg/sec, observed in the present study) is compatible with the range required for accurate identification of signs. In other words, the range of speeds in sign production appears to be guided by perceptual and motor constraints.

In addition, as for the spatial frequency content of articulators (discussed above), continual exposure to the specific range of speeds inherent in signs may affect deaf people's processing of non-linguistic motion stimuli. Specifically, deaf subjects may exhibit superior or enhanced processing of moving stimulus only within the range of speeds found in sign language. Recently, we investigated this possibility by measuring deaf signers' and hearing nonsigners' contrast sensitivity for moving stimuli across a range of speeds (Finney & Dobkins 2001). Although no differences between subject groups were found, we attribute this to the fact that the task involved merely detecting the presence of the stimulus rather than discriminating its direction or speed. Future studies in our laboratory will be conducted in order to determine whether group differences arise when subjects attend to the speed, direction, or orientation of the moving stimulus.

With regard to variations in speeds across signs, we found no differences in the median speed across different phonological categories. We did, however, find that maximal speeds were greatest for temporally inflected signs (see Figure 5). Aside from speed being a distinguishing feature between inflected and uninflected signs, speed has been argued to play a role in other morphological processes, such as comparative vs. superlative contrasts (Bellugi 1980) and for marking prominence in sentences (Wilbur 1999). Although the inflectional movement was limited to temporal inflections in the present study, our results suggest that a physical difference in the speed of signing between lexical and inflected movement may, in part, permit signers to treat lexical movements separately from inflected movements. Other features may be relevant as well, as suggested by Poizner's (1983) study using moving light emitting displays, where lexical movements were characterized by repetition and arcness, while inflected movement were characterized by cyclicity and displacement.

To conclude, these studies show that the spatial frequency and speeds of signs fall within a narrow range, suggesting that exposure to signs is a specific and unique visual experience. Further investigation is needed to confirm whether experience with these physical properties within the sign language signal enhances or alters visual sensitivity. Finally, the methodology and framework employed in this study can be used to explore and compare the visual and articulatory properties across various signed languages. Although the present study employed only signs from American Sign Language, it is quite likely that the range of spatial frequencies and speeds is fairly constant across different signed languages since the articulators, as well as motor and perceptual constraints, are expected to be common to all signers. This may be true despite the fact that overall hand configurations and motion trajectories are known to be quite varied across the different languages.

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Appendix

Study 1:

Analysis 1.

One-hand Signs:

ASK, CANADA, CAT, FACE, FIND, FOOD, GIVE, GIVE$_{\text{continuous}}$, HEART-FELT, KNOW, MAIL, MINE, SHUT-UP, SMART, SPIT, SUMMER, THROW, TELL, TELL$_{\text{continuous}}$, VOMIT

Two-hand Signs:

ARREST, BICYCLE, DESTROY, DOCTOR, ENJOY, GESTURE, HATE, HAVE, IMPROVE, LONG-AGO, READ, REJECT, REMOVE, SEND, SICK, STEAL, UNTIL, WASH-WINDOW, WONDERFUL, YEAR

Analysis 2.
Category 1: CANADA, DOCTOR, FOOD, HAVE, HEART, KNOW, MINE, SICK
Category 2: BICYCLE, ENJOY, GESTURE, LONG-AGO, $\text{READ}_{\text{continuous}}$, WASH-WINDOW
Category 3: GIVE, IMPROVE, READ, REJECT, SMART, TELL, UNTIL, VOMIT
Category 4: ARREST, ASK, CAT, FIND, HATE, REMOVE, RIP/DAMAGE, SEND, SHUT-UP, SPIT, STEAL, THROW

Study 2:

Category 1: CANADA, DOCTOR, FOOD
Category 2: BICYCLE, ENJOY, GESTURE, LONG-AGO, WASH-WINDOW
Category 3: HAVE, HEART-FELT, KNOW, MINE, SICK
Category 4: ARREST, ASK, CAT, FIND, HATE, MAIL, RIP/DAMAGE, SEND, SHUT-UP, SPIT, SUMMER, STEAL, THROW
Category 5: FACE, GIVE, IMPROVE, READ, REJECT, SMART, TELL, UNTIL, VOMIT, YEAR
Category 6: $\text{GIVE}_{\text{continuous}}$, $\text{READ}_{\text{continuous}}$, $\text{SICK}_{\text{continuous}}$, $\text{TELL}_{\text{continuous}}$

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