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A kinematic study of phonetic reduction in a young sign language

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ABSTRACT

Phonetic reduction arises in the course of typical language production, when language users produce a less clearly articulated form of a word. An important factor that affects phonetic reduction is the predictability of the information conveyed: predictable information is reduced. This can be observed in everyday use of reference in spoken language. Specifically, first mention of a referent is more carefully articulated than subsequent mentions of the same referents, which are often phonetically reduced. Here we ask whether phonetic reduction for predictable information exists in a young sign language, and, in particular, how phonetic reduction is realized in visual languages that exploit various articulators of the body: the hands, the head, and the torso. The only natural languages that we can observe as they emerge in real time are young sign languages, and we focus on one of these in the current study: Israeli Sign Language (ISL). We use 3D motion-capture technology to measure phonetic reduction in signers of ISL by comparing the production of referring expressions synchronically, at different points during a narrative (e.g., Introduction, Reintroduction, Maintenance). Our findings show: (a) that phonetic reduction is present in a young sign language; and specifically (b) that the actions of different articulators involved in discourse are reduced, based on predictability. We consider the importance of these findings in understanding predictability in language more generally.

1. Introduction

It is a well-known characteristic of speech that words are sometimes pronounced distinctly, e.g., 'memory' [mɛməri] and sometimes reduced, e.g, [mɛmri] (Bybee, 2001). Yet, cases like these are not an indication of random sloppiness; rather they are deviations in form which vary according to their predictability in sentences and in discourse (e.g., Heegård, 2012, 2013). With this perspective in mind, the aim of this paper is to investigate articulatory aspects of phonetic reduction in a young sign language, Israeli Sign Language (ISL), and to consider their occurrence in light of discourse contexts.

In spite of the relatively large number of studies of phonetic reduction in language (for an overview, see Ernestus & Warner, 2011), the interplay of factors of usage and of language age is under-investigated. In this paper, we demonstrate that signers reduce words which are repeated during the same discourse even in a young sign language, suggesting that reduction of predictable information is an early phenomenon in language emergence. By focusing on a sign language, this is one of the few studies to show that reduction of predictable information is not only cross-linguistic, but is also a cross-modal phenomenon.

Languages can be affected by two forces, the need for maximization of perceptual distinctiveness and the need for minimization of articulatory effort (Zipf, 1949). On the one hand, language must be expressive enough to communicate the message we wish to convey and to ensure that our interlocuters also perceive the message as intended. On the other hand, users strive to communicate this message in the most efficient way (Lindblom, 1963, 1990). One way in which the balance between expressivity and efficiency may be maintained is to reduce the production effort of the most predictable information conveyed. Speakers can shorten or merge words (Ernestus & Warner, 2011; Lieberman, 1963) or otherwise reduce the message acoustically (Aylett & Turk, 2004; Bard et al., 2000; Fowler, 1988; Fowler & Housum, 1987; Lam & Watson,

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2010). These phenomena are all included under the term **phonetic reduction**. A number of studies have attempted to reveal the patterns of occurrence of reduction phenomena, and describe the factors associated with phonetic reduction in speech (e.g., Bell et al., 2009; Clopper et al., 2017; Tendera et al., 2023). Among the investigated factors, predictability of (parts of) the utterance exerts significant influence on the presence and degree of phonetic reduction (Baker & Bradlow, 2009; Bell et al., 2009; Gundel et al., 1993; Turnbull, 2015).

The same pattern has been observed in predictable information in the visual gestures that accompany speech (Gerwing & Bavelas, 2004). Gestures accompanying predictable speech are less complex, less informative and less precise than gestures produced with unpredictable speech (Gerwing & Bavelas, 2004). For such gestures (often called co-speech gestures), predictable information is phonetically reduced compared to unpredictable information. The same tendency holds for natural languages which exist in the visual modality – sign languages of deaf people (Hoetjes et al., 2014; Mauk et al., 2008; Tyrone & Mauk, 2010). Specifically, predictable information is observed to be reduced in duration (Hoetjes et al., 2014) compared to unpredictable information.

The current paper explores the relationship between predictability and phonetic reduction in a young sign language, ISL, a language that is only about 90 years old (Meir & Sandler, 2008, in press). We begin in Section 2 with an overview of predictability and reduction of previously mentioned items in discourse. Following this, we introduce phonetic features in sign languages in Section 2.1, and then focus on phonetic reduction studies in sign languages (section 2.1.1). We then outline the studies relevant to phonetic reduction and predictability, especially in reference to participants in a discourse (section 2.2). In Section 3, we describe our innovative methodology, tracking the movements of deaf ISL signers by using 3D motion capture technology.

Our results (Section 4) show that there is a significant relationship between predictable information and phonetic reduction in a young sign language. In addition to manual articulations, we illustrate that head and torso movements are also reduced based on predictability of the information. This finding supports the Grammar of the Body view, that sign languages systematically recruit not only the hands, but other parts of the body as well (Sandler, Meir, et al., 2011; Sandler, 2012, 2018). We discuss these findings in light of predictability in language and how this is executed in a visual modality in Section 5.

2. Predictability & reduction

George Kingsley Zipf (1949) made the observation that highly frequent words (such as ‘the’) tend to be shorter than low frequency words. He proposed the Principle of Least Effort, in which language users simplify certain aspects of their language in order to minimize effort. One of the earliest, classic studies of phonetic reduction due to predictability and frequency was conducted by Lieberman (1963), in which he compared the duration and amplitude of the word “nine” when presented in the utterance “The number that you will hear is *nine*” and in the well-known proverb “a stitch in time saves nine.” “Nine” was produced with a longer duration, wider amplitude and more careful articulation, in the former utterance, in which the particular number, “nine”, is not predictable. In contrast, when “nine” was produced in the well-known proverb, it was reduced. This was attributed to predictability, i.e., to the conventionalization and automatization of the whole utterance as one unit. Following Lieberman (1963), other studies confirm that previously mentioned words are temporally reduced compared to words uttered for the first time, leading to reduction in length and intelligibility (Bard et al., 2000; Fowler, 1988; Fowler & Housum, 1987; Hawkins & Warren, 1994). It is the ‘previously mentioned’ forms of reduction which are the focus of this study and introduced in the following sections.

2.1. Phonetics in sign languages

Like spoken languages, sign languages are made up of sub-lexical elements that can be combined in different ways to form lexical items. A defining feature of sign language is that it uses the hands and arms, rather than the vocal tract organs, as its primary articulators. Stokoe (1960) identified three phonological parameters that can distinguish the sub-lexical level of signs in American Sign Language (ASL): handshape, movement, and location. Battison (1978) later added hand orientation—the direction that the palm faces—to this list. While the hands and arms are the primary articulators for sign language, movements of the head, face and torso also participate in conventionalized ways to structure linguistic information (Nespor & Sandler, 1999; Sandler, 2018).

The terms phonology and phonetics began in the context of research on spoken language; yet, nowadays neither term is used to refer to acoustic information alone (Tyrone & Mauk, 2012). While sign phonology focuses on the abstract features of signs that can create phonemic contrasts, sign phonetics deals with, among other issues, the relationship between the anatomy and physiology of the production system and the physical forms of lexical items, as well as the effects of phonetic context, prominence, phrase position, and production rate on the realization of lexical items. For example, Crasborn (2012) describes the phonetic form of the Sign Language of the Netherlands (NGT) sign, INDIA. Its phonological specification includes the forehead location, the extended thumb handshape, and a rotation movement of the thumb at the forehead. At the phonetic level, the state of more proximal joints (joints closer to the body, e.g., shoulder or elbow) will influence the location of the end of the extremity. In addition, bringing the tip of the thumb to the forehead (in other words, articulating the phonological location) will affect the non-manual features as well. It does not only involve a specific state of the shoulder, elbow, wrist, and thumb joints, but needs to take into account the current state of the upper body and head. When the head is turned rightwards, the hand will also need to be moved rightwards, for example by rotating the upper arm outwards. Thus, the phonetic effects of all the bodily articulators have to be accounted for.

An important branch of sign language phonetics has focused on the anatomy of the hand and arm in order to determine the inherent constraints on the formational structure of signs. Early studies examined handshapes in terms of their physiological and anatomical constraints (e.g., Ann, 1996; Mandel, 1981; Mandel, 1979). Following this, later research pursued the question of which joints of the hands, forearms and arms are flexed or extended to produce a sign (Brentari et al., 1995; Eccarius et al., 2012 inter alia). Few studies have looked at the phonetics of non-manual articulators (Udoff, 2014; Weast, 2008), or at the compensatory movements of the head and torso which facilitate contact with the hand during signing (Tyrone & Mauk, 2012, 2016). The present research aims to bridge this gap and to examine the phonetic effects of discourse context on various physical dimensions of several manual (hand/s) and non-manual (head and torso) characteristics. Despite the importance of facial expressions, they are unfortunately beyond the scope of this study.

2.1.1. Phonetic reduction studies in sign languages

In speech, a production is reduced if movements of the articulators are substantially smaller, or if the acoustic correlates of these movements undershoot their target values (Moon & Lindblom, 1994; Mooshammer & Geng, 2008). Similarly, an example of phonetic reduction in sign production can occur when the hand falls short of making contact ("undershoots") with a location on the body, or if lexical repetitions of the sign movement are deleted, or when movements become smaller than in the citation form (Tyrone & Mauk, 2012).

While phonetic reduction has rarely been explored in the sign modality, several studies have investigated coarticulation and other effects of phonetic context in signing (Cheek, 2001; Grosvald & Corina, 2012). In Sign Language of the Netherlands (NGT), Ormel, Crasborn, and van der Kooij (2017) used a data glove in conjunction with motion capture to investigate coarticulatory effects of hand height. They found that hand height was influenced by the location of the preceding and following signs. In addition, Russell et al. (2011) found that the extent of lowering differed in ASL according to the frequency of the sign that was lowered, with frequent signs lowered more often and to a greater extent.

Reduction can occur as an effect of production rate (Mauk, 2003; Tyrone & Mauk, 2010, 2012). Tyrone and Mauk (2010) examined the lowering of the sign 'wonder' in ASL by asking six participants to produce the sign at three different signing speeds. The results indicated that the signs were more likely to be lowered in higher speed environments, showing that signers reduce the size of the movements to compensate in high-speed environments. Using an Optotrak Certus motion capture system, in which signers wear infrared light-emitting markers, Tyrone and Mauk (2012) tracked the movements of four ASL signers producing four ASL signs located at the head. The location of the preceding and following signs (low & high phonetic environments) and the signing speed (slow, normal, fast) were manipulated. Lowering occurred more often and to a greater extent when the low phonetic environment was combined with faster signing rates. These studies (Mauk et al., 2008; Tyrone & Mauk, 2010) looked at the impact of signing rate on reduction (undershoot, location on the body) although not specifically at reduction of predictable information.

Head and torso movements were also examined by Tyrone and Mauk (2016) with the use of motion capture. Based on data elicited from five ASL signers, they found that for signs with a movement towards the head, the forehead and chin move to facilitate convergence with the hand. In contrast, the torso did not move to facilitate convergence with the hand for signs located at the torso. The authors concluded that the torso is less likely to show phonetic variation during signing than the head because of its heavier and larger size, and because moving the torso position requires the coordination of multiple muscle groups.

As is the case in spoken language studies too (Brouwer et al., 2013; Mitterer & Russell, 2013), the reduction of movement in sign languages has been associated with ease of articulation, and more specifically, a reduction of effort (Napoli & Liapis, 2019). Reduction of effort can be calculated by considering the force exerted for a given articulatory displacement (Kirchner, 1998, 2004). For example, smaller movements, which reduce the size of the sign, are claimed to be more articulatorily efficient (Napoli et al., 2014; Napoli & Liapis, 2019). Signers with Parkinson's disease undershoot on both handshape and location and they reduce the number of movements in a sign (Poizner et al., 2000). The authors suggest that since Parkinson's impacts motor planning and articulation systems, these changes in articulation serve as ways to reduce articulatory effort. A different amount of effort is exerted when moving different articulators. Because the torso is typically moved to mark grammatical information, such as segmenting intonational units (Nespor & Sandler, 1999; Sandler, 1999), discourse units (Boyes, 1999), questions (Neidle et al., 1997), or tenses (Aarons et al., 1992), it has been assumed that torso movement is unlikely to undergo articulatory change for effort reduction reasons (Napoli et al., 2014; Tyrone & Mauk, 2016).

2.2. Reduction of repeated references in discourse

When language users establish and maintain reference to relevant persons and objects in discourse, they often reduce repeated references compared to those that were previously introduced (Lieberman, 1963). Repeated references in discourse are often identified in terms of their referent status (Chafe, 1994). When a character is first introduced, the referent status is unknown and this is referred to as first mention or "Introduction" (Cormier et al., 2013). Reintroduction is defined as reference to the character which appears after a clause in which the referent is not mentioned. When the character is referred to again in the same passage without a change in topic, it is known as Maintenance – a reference which occurs after already appearing in the previous clause. Let's take an example, using the stimuli we will present in this study. In Example 1 below, when the character Charlie Chaplin is first introduced, he is referred to by using a proper name, articulated in its full phonetic form. Importantly, the discourse context known as Introduction typically presents less predictable information. Later in the discourse narrative, there is a change of topic – 'the lion' becomes the subject of the utterance, and then the character, Charlie, is referred back to, or reintroduced. In Maintenance, the character is referred to as 'Charlie' with reduced phonetic form. The spoken form of 'Charlie' in this instance is reduced, with a shortened vowel and thus a shorter overall length.

Example 1 (British pronunciation with r-drop)): **Charlie** [ʧɑːli] **[Introduction] Chaplin** ran from a donkey. **Charlie** [ʧəli] **[Maintenance]** ran straight into a lion's cage. The lion was sleeping. When **Charlie** [ʧɑːli] **[Reintroduction]** realized that he was locked in, he started to panic.

According to the the broader notion of referential hierarchies (Ariel, 1988, 1990; Givon, 1983; Gundel et al., 1993), language users create coherence by using less specific, less full referring expressions for the same entity, as they assume higher accessibility of the referent in the mind of the interlocutor as the discourse unfolds. The degree of reduction of referring expressions is directly related to the predictability of the information: the more predictable the information, the more it is reduced. Furthermore, predictability decreases as the distance from its last mention increases (Arnold, 1998; Arnold et al., 2009). Referents which are introduced are phonetically fuller than Reintroductions, and reintroduced referents are phonetically fuller than the maintained ones: Introduction > Reintroduction > Maintenance.

Several studies have investigated the reduction of predictable information in sign languages (Ferrara et al., 2022; Frederiksen & Mayberry, 2016; Hodge et al., 2019; McKee et al., 2011; Perniss et al., 2015; Wulf et al., 2002). Most of them focus on the choice of referring expressions such as ‘Charlie-Chaplin’, ‘the man’, or pronouns, such as ‘he’, rather than phonetic reduction. For example, a study looking at signers of German Sign Language showed that maintained references were accompanied by leaner referring expressions, such as pronouns, and reintroduced references by fuller referring expressions, such as nouns (Perniss et al., 2015). Frederiksen and Mayberry (2016) analyzed four simple narratives produced by eight native American Sign Language (ASL) signers, and examined how the signers tracked reference throughout their narratives. They found that Introductions were marked with fuller, more explicit referring expressions than Reintroductions, and Introductions were marked with more explicit referring expressions than maintained references. However, their study found no significant difference between maintained and reintroduced references. We return to this point in our own findings in the Discussion.

Fewer studies have focussed on *phonetic reduction* of predictable information in sign languages more specifically. One study on Sign Language of the Netherlands, examined phonetic reduction of repeated references by fourteen signers (Hoetjes et al., 2014). In their task, participants were asked to describe images (e.g., pictures of people, furniture) to another participant who had to select the correct image from a group of images. Repeated productions were shorter, contained fewer signs, and shorter signs than initial references, in line with spoken language studies (Bell et al., 2009; Clark & Wilkes-Gibbs, 1986). In a recent study looking at reduction of fingerspelled and core lexical signs in ASL, Martinez del Rio (2023) found that in addition to reduction in duration, there was deletion of movements and the centralization of the location of signs articulated on the body.

2.3. The current study

In this study, we examine phonetic reduction of repeated referring expressions over the course of a single discourse, considering the contribution of different articulators, including the hand, head and body, and different movement parameters such as volume, speed and duration. We inquire (1) whether reduction of predictable information is observed in a young signed language. To this end, we utilize the advances of 3D motion capture technology in order to quantifiably measure phonetic reduction in a sign language in a non-invasive manner. Research on spoken languages, including early research by Lieberman (1963), exploited the use of spectrograms in order to acoustically measure the spectrum of frequencies of a signal as it varies with time. In contrast, in signed language studies, there has been a lack of objective instrumental measures for quantifying phonetic reduction (except Ormel et al., 2017; Tyrone & Mauk, 2012), which we correct in this study. We also ask: (2) which specific kinematic features vary in relation to the predictability of information?

Most studies to date on phonetic reduction have focused their attention on the hands (Hoetjes et al., 2014). However, signers also use the head (Dachkovsky et al., 2013; Lackner, 2015; Puupponen, 2018; Sandler, Aronoff, et al., 2011), and torso (Crasborn & Ormel, 2011; Wilbur & Patschke, 1998; Sandler, 2018) to convey linguistic information, and in particular referential information (Stamp & Sandler, 2021). Studies also show that movement production of different articulators incurs different degrees of articulatory effort (Napoli et al., 2014). We also ask: (3) are the head and the torso involved in signaling referent status in signed languages, and do their articulations reduce when referential status is predictable? To address these questions, in addition to the hands, and following The Grammar of the Body Paradigm (Sandler, Meir, et al., 2011; Sandler, 2012, 2018), we examine the whole body, including the head and torso, in terms of reference and phonetic reduction.

3. Method

In the following sections, we describe the community under investigation, including the participants and task, as well as the methods adopted using motion capture technology.

3.1. The Israeli deaf community

The community under investigation in this study is the Israeli deaf community whose preferred language is Israeli Sign Language (ISL), a young sign language which emerged naturally only about 90 years ago (Meir & Sandler, 2008). ISL arose with the formation of the Israeli deaf community in the 1930s, beginning with the establishment of the first school for deaf children in 1932 in Jerusalem. Immigrants from all over the world contributed to the signing used by a small number of deaf Jews and Arabs already in Jerusalem. A conventionalized signed language evolved over the last three generations, and today, ISL is used by approximately 10,000 signers in a wide range of settings, including the educational system, deaf social and cultural institutions, interpreting programs, and the media.

3.2. Participants & task

Fifteen participants were recruited for this study from a range of ages. All participants are deaf signers whose preferred language is ISL. Participants were filmed in a seated position[1] completing a series of tasks. Of these, only the narra-

[1] Participants were filmed seated in order to provide a natural environment. In addition, we wanted to keep the filming set-up consistent across participants – since all participants were involved in a series of tasks and some participants were older, it was not possible to film them standing.

tive retelling task is analyzed for this study. As part of this task, participants were asked to watch an edited segment of ‘The Lion’s Cage’ taken from Charlie Chaplin’s silent movie ‘The Circus’ (1928), and to retell the events of the stories to an interlocutor, another deaf signer matched for age, who did not see the same video segment.

In this segment (3min 23s), Charlie Chaplin finds himself trapped in a lion’s cage. In his attempt to free himself, Chaplin interacts with a number of different characters and engages in a number of actions. In the end, a woman rescues Chaplin by opening the cage and setting him free. In order to elicit a detailed narrative, signers were informed that their interlocutors would complete a comprehension task after their retelling, which involved ordering five still shots extracted from the movie, in chronological order of the events as they were described to them. The motions of each signer were tracked using two Microsoft Kinect motion capture cameras, as described in Section 3.3 below. Two participants were excluded from the analysis as the motion capture data were unanalyzable. Of the 13 participants remaining, there were seven females and six males (age range 25–76 years). Narrative retellings varied from 1min 23s to 4min 27s (mean: 2min 42s). A total of 36min 17s were analyzed, eliciting specifically referent Introductions, Reintroductions and Maintenances.

3.3. Kinect motion capture technology

To track the motions of our signers, a Kinect Version 2 (V2) motion capture system was employed. The Kinect V2 (Microsoft, 2018) is a portable 3D camera capable of recording depth information using Time of Flight technology (Foix et al., 2011; Hansard et al., 2012). The camera is controlled by a laptop on which the recorded data was also stored. The Kinect camera captures a video stream of 3D point clouds (often referred to as depth images) in which every pixel value represents the distance from the camera. Fig. 1 shows an example of one such captured frame which shows the brighter pixels further in distance from the camera.

In addition, when a human subject is recorded, the system supplies a skeleton representation of the subject computed per frame from the point cloud (Shotton et al., 2011). The skeleton data includes 25 major skeleton joints, connected by line segments. Fig. 2 shows the layout of the skeleton with the joints labelled. For every frame, the system gives an output with the 3D locations of the 25 skeleton joints (a triplet (x,y,z) in meters, given in the camera's frame of reference). For visualization only, we plot these 25 points by projecting them onto an image plane (e.g., disregarding the z-coordinate and plotting the joint at the x-y coordinates), and connecting the bones of the corresponding points in the image. Fig. 3 shows an example. The signers were recorded while signing, and both RGB images and the 3D skeleton data were captured per frame. The advantage of using a depth camera such as the Kinect V2 is that it is neither intrusive nor invasive. There is no need for attaching reflectors or sensors to the body (as in other systems such as the Vicon tracking system), which may inhibit or affect signing in an unnatural way.

Kinect tracking error is small compared to the movements performed by the signers. Kinect errors are in the range of 0.5–2cm (Fankhauser et al., 2015) whereas our features

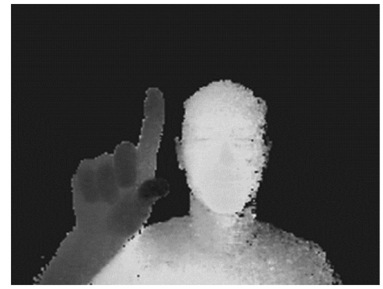

Fig. 1. A 3D point cloud (depth image) captured by the Kinect V2.

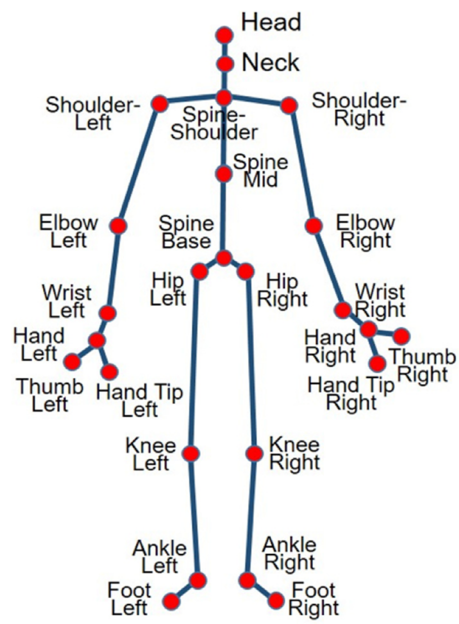

Fig. 2. Skeleton of human subject consisting of 25 points.

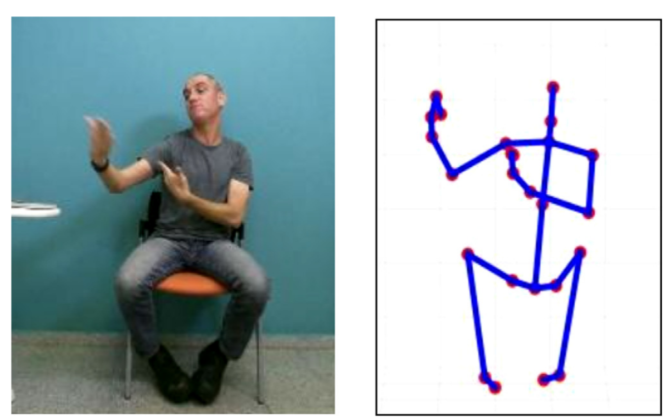

Fig. 3. Image of signer (left) and the corresponding 3D skeleton – joints indicated by red circles, connected by line segments (right).

(see below) are on a larger scale: the mean values of our hand features are 55cm for the distance, 757cm^3 for the volume, and 25cm for the mean distance from the body. Furthermore, the Kinect noise is approximately zero mean (Privman-Horesh et al., 2018). Thus, the errors do not (statistically) accumulate and at most the error on the accumulated distances, volume and other features are on the order of two frame errors (e.g., first and last frames of the accumulations). All possible precautions were taken to reduce errors. For example, a uniform dark-coloured backdrop was used to improve tracking.[2]

From the skeleton data, we extract spatio-temporal features associated with signing and we use these in our analysis. The full recording sessions were dissected into segments, each comprised of a single sign or action. For each segment to be analyzed, a sequence of skeletons (frames) was captured. Various measurements were computed per skeleton frame and then combined to produce a set of measurements representing the whole segment. The choice of measurements was based on previous studies which looked at kinematic differences in signed (Tyrone & Mauk, 2010) or gestural data (Namboodiripad et al., 2016). Prior to computing the measurements, the skeletons were normalized to a standard size using the method in Weibel et al. (2016) to eliminate size effects. In the following, we briefly describe the collected measurements. Since the skeleton joints are reported per video frame, each joint in this equation is indexed by the frame number. For a skeleton joint p, we track its 3D location per frame i: $p_i = (x_i, y_i, z_i)$ and compute the following measures across the N frames of the segment:

- *Duration* (D) – the time elapsed in seconds between the first and last frames in the sequence.
- *Distance Covered* (DC(p)) – the distance in meters, traversed by the skeleton joint p during the sequence. It is computed by accumulating the Euclidean distance between joint location in consecutive frames.[3]
- *Average speed* (S(p)) – computed as the Distance Covered by joint p divided by the duration. speed is given in m/s:

$$S(\mathrm{p}) = \frac{DC(\mathrm{p})}{D}$$

- *Variance* (std squared σ^2(p)) of Location – the variance of the 3D position of the joint p across the sequence (meters^2).
- *Volume* (V(p)) – the 3D volume of the space (meters^3) traversed by joint p during the sequence. It is computed by determining the volume of the smallest convex polygon that bounds all 3D locations of the joint p throughout the sequence (Preparata & Hong, 1977).
- *Mean distance from body plane* (*DB*(p)) – the distance in meters of the skeleton joint from the body plane. The body plane is computed as the 2D plane spanned by three skeleton joints: Shoulder-Left, Shoulder-Right and Spine-Base (see Fig. 2). Marking these joints as p1, p2, p3 respectively the plane normal *Pl* (unit vector) is then given by:

$$Pl = \frac{(p1 - p3)X(p2 - p3)}{\|(p1 - p3)\|_2 \|(p2 - p3)\|_2}$$

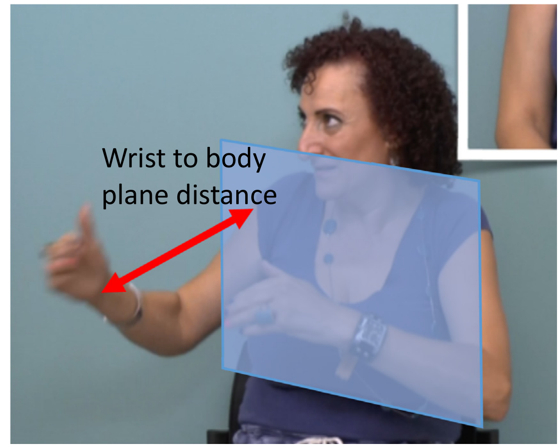

Fig. 4. Distance from skeleton joint to body plane, for example: wrist joint to body plane.

The denominator normalizes the vectors to produce a unit vector *Pl*.

The distance from joint p to the body plane is measured along the line perpendicular to the plane and passing through the joint (see Fig. 4)[4]:

$$DB(p) = |p^{\circ} Pl|$$

Results were analyzed using these six measures collected from three joints of the skeleton: (1) head movement was analyzed using the head joint, (2) the hands were analyzed using the signer's dominant hand joint (right or left), and (3) the torso was analyzed using the spine-shoulder joint at the top of the spine (see Fig. 2).

3.4. Data coding

All examples for the signs CHARLIE-CHAPLIN, LION, and WOMAN were extracted from the narratives (see Fig. 5). 211 examples were collected, according to discourse context: 38 Introductions, 149 Reintroductions and 24 Maintenances.

These referring expressions were categorized by referent status according to Cormier et al. (2013).

1) Introduction: First mention of a referent, independent of clause position
2) Reintroduction: A referent appearing (as topic in the current clause) subsequent to a clause where the referent was not mentioned
3) Maintenance: A referent that appeared in any position in the previous clause appearing in the current clause (as topic)

Two of the authors, non-native hearing signers, together with a deaf native ISL signer, coded all of the data, locating all of the relevant lexical signs and their discourse contexts. Cross-coder reliability for the discourse context category reached 95% agreement. The first frame of each sign was determined based on the moment at which the target handshape and orientation were obtained. In turn, the last frame

[2] Depth cameras are in essence insensitive to color and textures so that the colour of background or clothing does not affect motion capture. That said the system may show errors when background colors are similar to body colors (beige and skin tones).

[3] This is a common method for measuring smooth paths and manifolds. Due to the high frame rate of the Kinect (30fps) and the smooth motion paths of the joints, this is a very good approximation of the length of the real-world motion path.

[4] For the hand and head joints, the body plane is computed in each frame, however for the torso (spine-shoulder joint), the Distance-to-body is calculated relative to the body plane computed in the first frame of the sequence in order to capture the body motion relative to the neutral pose in the first frame.

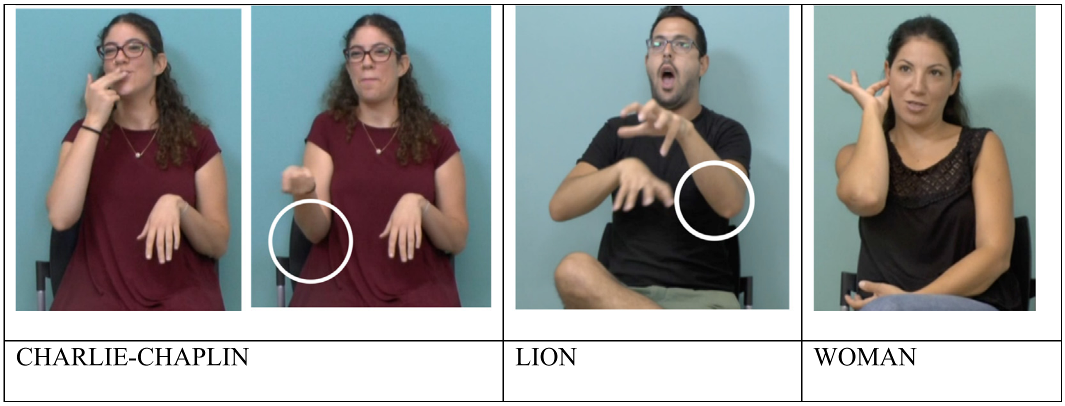

Fig. 5. Examples of the three lexical items under investigation, circles represent the circular motion of the wrist in CHARLIE-CHAPLIN and the alternating motion of the two hands in LION.

of each sign was determined as the frame which precedes a switch in the target sign handshape.

All recorded sequences were processed to calculate a set of motion-related measures. Specifically, the recorded 3D skeleton data collected by Kinect were analyzed, and the kinematic parameters were computed for the three joints. The python code for extracting Kinect V2 features is found on Open Science Framework (OSF): https://osf.io/bn5mg/.

3.5. Data analysis

Separate analyses were conducted for each articulator – the hand, the head and the torso – and therefore in total eighteen linear mixed models were performed. We conducted linear mixed models[5] using SAS version 9.4 procedure GLIMMIX to determine whether there is a relationship between each kinematic parameter (i.e., duration, distance covered, speed, variance, volume and mean distance from the body plane), as the dependent variable, and two independent variables: discourse contexts (i.e., Introduction, Reintroduction and Maintenance), and lexical item (i.e., Charlie-Chaplin, girl, lion). Participant was included as a random intercept. We also tested for an interaction between discourse contexts and lexical item. Note, any insignificant interactions were removed from the model and it was re-run without the interaction, to reduce the complexity of the model. One of the assumptions of the model is that the residual error is normally distributed. Since the model did not meet this assumption for some parameters, these were transformed into a log-normal distribution (duration, distance covered, speed_head, speed_torso, variance and volume). Post hoc tests, adjusted for multiple comparisons with Bonferroni corrections, were run to explain the differences between the discourse contexts.

4. Results

We expect to see that if reduction occurs the sign will be reduced in length, reflected in duration and distance covered, and size, reflected in variance and volume. We do not expect to see a reduction in the speed of the movement. We show the relationship between each kinematic parameter, including discourse context (that is, Introduction, Reintroduction and Maintenance) and lexical item as independent variables in Section 4.1. Following this, we present the post hoc analysis in Section 4.2 and also the direction of the discourse context differences.

4.1. Statistical analysis

As shown in Table 1, there were no significant interactions between discourse contexts and lexical item. The six kinematic parameters were analyzed per articulator (hand, head, torso), resulting in a total of eighteen separate linear mixed models. The F and p values indicate how well the model can discriminate across the discourse contexts for each parameter separately (displayed in Table 1).

The results show that Discourse contexts and Lexical Item were significant predictors for duration (hand, head, torso), distance covered (hand), and volume (hand, torso). Discourse context was significant, without lexical item, only for distance covered (head, torso), variance (hand, head, torso), and volume (head). In addition, no interactions were found between discourse context and lexical item. Lexical item alone was significant for speed (hand, head) and mean distance from the body plane (hand). No significant predictors were found for speed (torso) and mean distance from the body plane (head, torso).

For those results related to lexical item, there are fundamental differences between the three lexical signs under investigation; for instance, 'Charlie-Chaplin' is consistently longer, faster, and larger than 'girl' and 'lion', and 'lion' was consistently further away from the body plane than 'Charlie-Chaplin' or 'girl'. These differences relate directly to the different types of movements within each sign. Since our focus is on the discourse context in this paper, we only present the post hoc analyses (in sections 4.1.1, 4.1.2. 4.1.3) and the means and standard errors (in Table 2), based on the discourse contexts results alone.

Table 2 above presents the mean and standard errors for the discourse contexts differences.

In Fig. 6, the estimates and standard errors are plotted in graphs, with upper and lower limits.

[5] For the purposes of reproducibility, here is an example of the variables included in one analysis: head duration ~ IMR(discourse context) + lexical_item + IMR*lexical_item + (1|participant) – interpreted as 'head duration' as the dependent variable, discourse context and lexical item as independent variables and participant as random intercept.

Table 1
Results of eighteen linear mixed models.

Dependent variable	Independent variables	Hand	Head	Torso
Duration (s)	Discourse contexts	**F(2,194) = 31.25, p < .0001**	**F(2,194) = 19.04, p < .0001**	**F(2,194) = 19.04, p < .0001**
	Lexical_item	**F(2,194) = 7.87, p = .0005**	**F(2,194) = 5.04, p = 0.0074**	**F(2,194) = 5.04, p = .0074**
	Effect size	R2m = 0.253	R2m = 0.177	R2m = 0.177
Distance covered (m)	Discourse contexts	**F(2,194) = 14.6, p < .0001**	**F(2,194) = 6.5, p = .0018**	**F(2,194) = 4.8, p = .0092**
	Lexical_item	**F(2,194) = 4.63, p = .0108**	F(2,194) = 0.46, p = .6330	F(2,194) = 0.08, p = .9257
	Effect size	R2m = 0.149	R2m = 0.054	R2m = 0.0404
Speed (m/s)	Discourse contexts	F(2,194) = 0.61, p = .5458	F(2,194) = 0.36, p = .6986	F(2,194) = 0.24, p = .7876
	Lexical_item	**F(2,194) = 6.09, p = .0027**	**F(2,194) = 5.94, p = .0031**	F(2,194) = 2.69, p = .0706
	Effect size	R2m = 0.0447	R2m = 0.0496	R2m = 0.0257
Variance (m^2)	Discourse contexts	**F(2,194) = 13.74, p < .0001**	**F(2,194) = 6.15, p = .0026**	**F(2,194) = 4.82, p = .009**
	Lexical_item	F(2,194) = 0.54, p = 5856	F(2,194) = 0.43, p = .6504	F(2,194) = 0.06, p = .9394
	Effect size	R2m = 0.107	R2m = 0.0511	R2m = 0.0398
Volume (m^3)	Discourse contexts	**F(2,194) = 16.9, p < .0001**	**F(2,194) = 8.67, p = .0002**	**F(2,194) = 12.31, p < .0001**
	Lexical_item	**F(2,194) = 5.97, p = .0031**	F(2,194) = 0.32, p = 7262	**F(2,194) = 12.31, p < .0001**
	Effect size	R2m = 0.177	R2m = 0.0649	R2m = 0.0941
Mean distance from body plane (m)	Discourse contexts	F(2,194) = 0.05, p = .9477	F(2,194) = 0.67, p = .5116	F(2,194) = 1.28, p = .2812
	Lexical_item	**F(2,194) = 160.95, p < .0001**	F(2,194) = 0.73, p = .4850	F(2,194) = 1.01, p = .3657
	Effect size	R2m = 0.576	R2m = 0.0104	R2m = 0.0160

Table 2
Means and standard errors for discourse contexts results.

		Hand	**Head**	**Torso**
Duration (s)	Intro	M = 0.6141	M = −0.7262	M = −0.7262
		Se = 0.04350	Se = 0.1179	Se = 0.1179
	Main	M = 0.3107	M = −1.3921	M = −1.3921
		Se = 0.05341	Se = 0.1461	Se = 0.1461
	Reintro	M = 0.2928	M = −1.4286	M = −1.4286
		Se = 0.03140	Se = 0.08211	Se = 0.08211
Distance covered (m)	Intro	M = −0.8689	M = −3.0920	M = 3.5370
		Se = 0.1462	Se = 0.1869	Se = 0.2067
	Main	M = −1.6952	M = −3.7701	M = −4.0586
		Se = 0.1821	Se = 0.2286	Se = 0.2549
	Reintro	M = −1.6320	M = −3.6943	M = −4.1493
		Se = 0.09901	Se = 0.1369	Se = 0.1468
Speed (m/s)	Intro	M = −0.1429	M = −2.3660	M = −2.8109
		Se = 0.09716	Se = 0.1517	Se = 0.1625
	Main	M = −0.3053	M = −2.3782	M = −2.6663
		Se = 0.1218	Se = 0.1860	Se = 0.2006
	Reintro	M = −0.2012	M = −2.2687	M = −2.7224
		Se = 0.06342	Se = 0.1103	Se = 0.1149
Variance (m^2)	Intro	M = −2.9742	M = −6.7977	m = −7.5828
		Se = 0.3012	Se = 0.3992	se = 0.4436
	Main	M = −4.4609	M = −8.1366	M = −8.6252
		Se = 0.3668	Se = 0.4867	Se = 0.5435
	Reintro	M = −4.3832	M = −8.0482	M = −8.8723
		Se = 0.2237	Se = 0.2954	Se = 0.3227
Volume (m^3)	Intro	M = 4.8350	M = −1.7679	M = −2.5554
		Se = 0.3602	Se = 0.3489	Se = 0.2665
	Main	M = 2.5429	M = −3.0239	M = −3.5373
		Se = 0.4534	Se = 0.4152	Se = 0.3157
	Reintro	M = 2.7268	M = −2.9595	M = −3.6439
		Se = 0.2284	Se = 0.2760	Se = 0.2129
Mean distance from body plane (m)	Intro	M = 0.2112	M = −3.5668	M = 0.02769
		Se = 0.01020	Se = 0.1656	Se = 0.003224
	Main	M = 0.2106	M = −3.3548	M = 0.02471
		Se = 0.01250	Se = 0.2035	Se = 0.003762
	Reintro	M = 0.2084	M = −3.4385	M = 0.02910
		Se = 0.007436	Se = 0.1193	Se = 0.002661

4.2. Post hoc analyses

We performed post hoc analyses, using Bonferroni adjustment (due to multiple comparisons). There were significant differences between Introduction and Reintroduction for all kinematic parameters, except speed and mean distance from body plane. This finding was true for all articulators: hand, head and torso. Similarly, there were significant differences between Introduction and Maintenance for all kinematic parameters, with the exception of speed and mean distance from body plane. In this case, the same result was found for the hand and head but not for torso in the measures of distance covered and variance. Notably, there were no significant differences between Maintenance and Reintroduction for every kinematic parameter. Speed and mean distance from the body plane were not predicted by discourse contexts, which is clear in the visualization in Fig. 6. Introductions are longer in duration and distance covered, and larger in variance and volume, in all

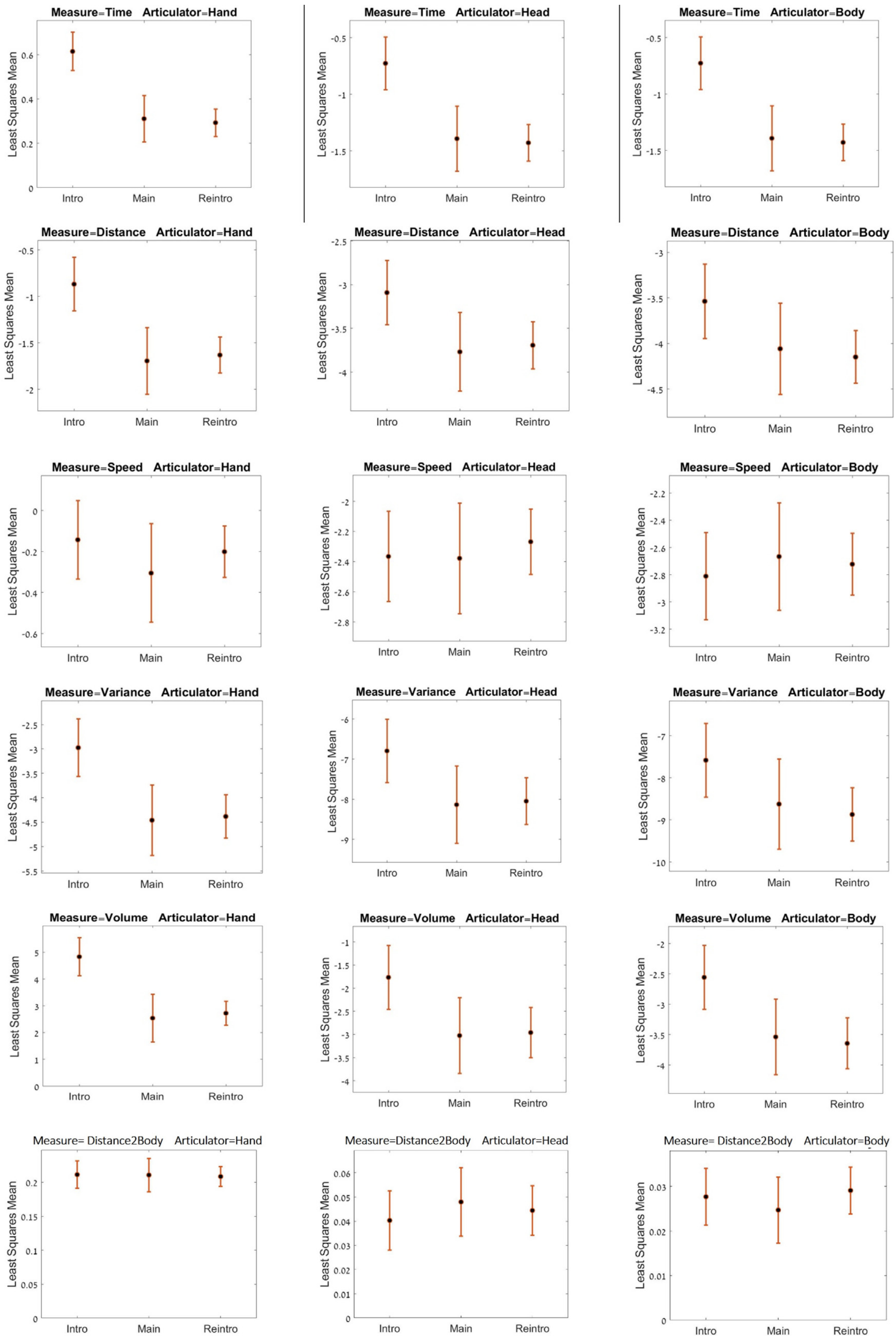

Fig. 6. Graphs for eighteen analyses, as labelled.

cases. Table 3 presents the results for all kinematic parameters for all three articulators, including the estimates and adjusted p values. Significant results are presented in bold.

5. Discussion

This study was the first of its kind to look at phonetic reduction in a young sign language, and the first to integrate the articulation of hands, head, and torso. We asked three research questions: (1) Is reduction of predictable information observed in a young sign language? (2) Which specific kinematic features vary in relation to the predictability of referents? and (3) Are the head and the torso involved in signalling referent status in sign languages, and do their articulations reduce when referential status is predictable? The findings of the study are summarised in Table 4 below.

We found evidence of phonetic reduction in ISL, a young sign language used in Israel. The evidence manifested in specific kinematic parameters and across different articulators. We found reduction of the sign in terms of the parameters which relate to length and size and not in terms of movement speed or the distance from the body. The findings clearly showed that referring expressions in ISL are phonetically reduced over the course of a signed narrative, in terms of sign duration, distance covered, variance and volume (section 5.1). As noted, while previous studies of sign languages have focussed on the hands, our study also points to the reduction in movement of the head and torso, providing further evidence for the importance of these articulators in sign language analysis (section 5.2). Finally, reduction is found between Introductions and Reintroductions, and Introductions and Maintenance, but not between Reintroductions and Maintenance (section 5.3). These findings point to some interesting conclusions, which we discuss in more detail below.

5.1. Predictable signs are reduced in duration and volume

The measures selected for this study were based on previous studies focussing on sign language variation including duration, distance covered, speed, variance, volume, and mean distance from the body plane. Similar to previous studies in spoken languages (Clark & Wilkes-Gibbs, 1986; Galati & Brennan, 2010) and in signed language (Grosjean, 1979; Hoetjes et al., 2014), this study also found that predictable information was reduced in terms of duration and distance covered. Our result supports previous findings, which show that discourse mention leads to word reduction in spoken language (Clopper et al., 2017; Lam & Watson, 2010). In sign languages, Grosjean (1979) found that repeated signs were reduced in duration by an average of 10%. In Fig. 7, for example, we see two examples of the same sign ‘lion’, one produced when the lion is first mentioned and the other when the lion is reintroduced. The distance covered, a measure used to track the exact path covered by the hand, is twice as long for the Introduction (0.979m) than for the Reintroduction (0.429m), showing a stark reduction upon repetition in the discourse. This can be seen by the length of the pink line shown in Fig. 7 below.

There is a clear relationship between duration and distance covered in that, as duration increases, it is likely that distance covered will increase too, however, one measure can act independently of the other – duration can increase while distance covered can remain static. Therefore, these parameters were both analyzed independently, however, the fact that duration and distance covered were often both significant, is not surprising. This may also explain similarities in findings between variance and volume.

Variance and volume were also found to be important variables in phonetic reduction in this study, similar to previous studies (Tyrone & Mauk, 2010). In Fig. 8, the volume is shown as a black cage projected from the right hand, showing the accumulative 3D volume. In this example, the volume of the Introduction of Charlie Chaplin is 6161cm^3, while the Reintroduction is significantly smaller, measured as 100cm^3 and the Maintenance example is only 1.4cm^3. The finding that the volume or size of the signing space reduces with increased predictability may be associated with ease of articulation through a reduction in effort (Napoli et al., 2014). According to Napoli and colleagues (2014), effort in sign languages can be calculated by measuring the force exerted for a given articulatory displacement (Kirchner, 1998, 2004). It has been shown that smaller movements, which reduce the duration and size of the sign, are articulatorily more efficient than larger ones (Napoli et al., 2014; Poizner et al., 2000).

5.2. Head and torso movements are reduced

While previous studies in sign languages have focussed on the hands (Hoetjes et al., 2014), our study points to the importance of analysing the movement of the head and torso in addition. Our findings support Tyrone & Mauk’s study (2016), in which they found that while the head was engaged in phonetic variation by moving towards the hand when signs were located at the head, the torso was not. Our study shows the importance in also considering torso movement when examining phonetic reduction. When looking at specific examples incorporating head and torso movements, we see that some signers accompany an Introduction of the referent with head and torso movements which reflect the character of the referent, a feature referred to as constructed action (Cormier et al., 2013, 2015). For example, the lexical sign CHARLIE-CHAPLIN was articulated together with a repeated wiggle of the head and torso from side to side, depicting the iconic movements of Charlie Chaplin. In later repetitions, these movements were missing. Therefore, the exact form of the movements and their relative functions warrant further investigation.

Despite the importance of the torso, we did see less reduction of the torso movement compared to the head and furthermore, less reduction of head movement compared to the hand. While we see a difference in terms of distance covered for the hands and head between Introduction and Reintroduction, we only see a difference between Introduction and Maintenance when analyzing the torso movement. This might be attributed to a number of factors. One suggestion is the relative size of each articulator – as the size of the articulator increases, it may be more difficult to signal phonetic reduction. Tyrone and Mauk (2016) claim that the torso is less likely to show phonetic variation during signing because of its heavier and larger size in comparison to smaller articulators such as the hands and head. The size of the articulator has been shown to be an important factor in other sign language studies (Dachkovsky et al., 2022).

Table 3
Post hoc results.

	Articulator	I-R	I-M	M-R
Duration	Hand	**t(194) = 7.83, est: 0.3213, adj. p < .0001**	**t(194) = 5.1, est: 0.3034, adj. p < .0001**	t(194) = 0.35, est: 0.0179, adj. p = 1
	Head	**t(194) = 6.11, est: 0.702, adj. p < .0001**	**t(194) = 4, est: 0.665, adj. p = .0003**	t(194) = 0.25, est: 0.036, adj. p = 1
	Torso	**t(194) = 6.11, est: 0.702, adj. p < .0001**	**t(194) = 4, est: 0.665, adj. p = .0003**	t(194) = 0.25, est: 0.036, adj. p = 1
Distance covered	Hand	**t(194) = 5.24, est: 0.763, adj. p < .0001 t(**	**t(194) = 3.92, est: 0.8263, adj. p = .0004**	t(194) = −0.35, est: −0.063, adj. p = 1
	Head	**t(194) = 3.47, est: 0.602, adj. p = .002**	**t(194) = 2.69, est: 0.678, adj. p = .0234**	t(194) = −0.35, est: −0.075, adj. p = 1
	Torso	**t(194) = 3.09, est: 0.612, adj. p = .0068**	t(194) = 1.82, est: 0.521, adj. p = 2127	t(194) = 0.37, est: 0.090, adj. p = 1
Speed	Hand	t(194) = 0.59, est: −0.305, adj. p = 1	t(194) = 1.13, −0.142, adj. p = .7786	t(194) = −0.85, est: −0.201, adj. p = 1
	Head	t(194) = −0.68, est: −0.097, adj. p = 1	t(194) = 0.06, 0.012, adj. p = 1	t(194) = −0.62, est: −0.109, adj. p = 1
	Torso	t(194) = −0.57, est: −0.088, adj. p = 1	t(194) = −0.64, est: −0.144, adj. p = 1	t(194) = 0.29, est: 0.056, adj. p = 1
Variance	Hand	**t(194) = 5.11, est: 1.409, adj. p < .0001**	**t(194) = 3.71, est: 1.486, adj. p = .0008**	t(194) = −0.23, est: −0.077, adj. p = 1
	Head	**t(194) = 3.41, est: 1.191, adj. p = .0024**	**t(194) = 2.51, est: 1.256, adj. p = .0384**	t(194) = −0.19, est: −0.064, adj. p = 1
	Torso	**t(194) = 3.10, est: 1.289, adj. p = .0066**	t(194) = 1.73, est: 1.042, adj. p = .2557	t(194) = 0.48, est: 0.237, adj. p = 1
Volume	Hand	**t(194) = 5.64, est: 2.292, adj. p < .0001**	**t(194) = 4.23, est: 2.108, adj. p = .0001**	t(194) = −0.40, −0.183, adj. p = 1
	Head	**t(194) = 4.06, est: 1.191, adj. p = .0002**	**t(194) = 2.94, est: 1.256, adj. p = .0109**	t(194) = −0.17, est: −0.064, adj. p = .8615
	Torso	**t(194) = 4.93, est: 1.088, adj. p < .0001**	**t(194) = 3.06, est: 0.981, adj. p = .0075**	t(194) = 0.39, est: 0.106, adj. p = 1
Mean distance from body plane	Hand	t(194) = −0.3, est: −0.019, adj. p = 1	t(194) = −0.89, est: −0.085, adj. p = 1	t(194) = 0.79, est: 0.065, adj. p = 1
	Head	t(194) = −0.82, est: −3.354, adj. p = .1	t(194) = −0.93, est: −3.566, adj. p = .1	t(194) = −0.43,est: −3.438, adj. p = 1
	Torso	t(194) = −0.56, est: −0.001, adj. p = 1	t(194) = 0.81, est: 0.002, adj. p = 1	t(194) = −1.39, est: −0.004, adj. p = 1

Table 4
Summary of results (with differences between Introduction (I), Reintroduction (R) and Maintenance (M)).

	Articulator	I-R	I-M	M-R	Direction
Duration	Hand	Yes	Yes	No	Intro > reintro/main
	Head	Yes	Yes	No	Intro > reintro/main
	Torso	Yes	Yes	No	Intro > reintro/main
Distance covered	Hand	Yes	Yes	No	Intro > reintro/main
	Head	Yes	Yes	No	Intro > reintro/main
	Torso	Yes	No	No	Intro > reintro/main
Speed	Hand	No	No	No	–
	Head	No	No	No	–
	Torso	No	No	No	–
Variance	Hand	Yes	Yes	No	Intro > reintro/main
	Head	Yes	Yes	No	Intro > reintro/main
	Torso	Yes	No	No	Intro > reintro/main
Volume	Hand	Yes	Yes	No	Intro > reintro/main
	Head	Yes	Yes	No	Intro > reintro/main
	Torso	Yes	Yes	No	Intro > reintro/main
Mean distance from body plane	Hand	No	No	No	–
	Head	No	No	No	–
	Torso	No	No	No	–

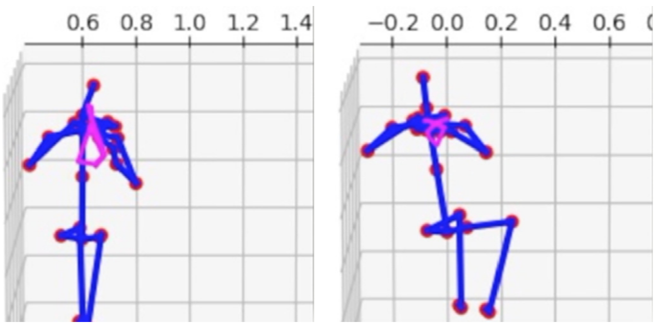

Fig. 7. An example of the distance covered (the pink line) for the sign LION in Introduction = 0.979 m (left), and Reintroduction = 0.429 m (right).

We might also attribute this finding to the degree of overall movement contributed by each articulator during the production of a typical sign. The movement of the hands is the greatest, followed by other articulators, such as the head, and torso, with less involvement from larger articulators. It is claimed that this relationship exists based on functional characteristics of different articulators (Cassell et al., 2001; Kendon, 1972). Because the tissues and muscles located on the torso are larger than those in the neck and face (e.g., Baker-Shenk, 1983; Prendergast, 2013), there are fewer torso movements compared to face and head movements.

Moreover, in this study, participants were filmed while seated, and therefore the movement of the torso may have been more restricted compared to the head and hands. Despite this relational trend, the findings show that linguists can still look beyond hand movements to understand phonetic reduction patterns in signed languages.

5.3. No difference between examples of Reintroduction and Maintenance

One important finding in this study was the fact that there was no significant difference in phonetic reduction between examples of Reintroduction and Maintenance. As summarized in Table 3, Introductions were significantly longer in duration and distance covered, and larger in variance and volume, than examples of Reintroductions and Maintenances. Despite the fact that reintroduced referents are less predictable than maintained referents, there was no significant difference found in terms of phonetic reduction.

Studies claim that there is a hierarchy for referring expressions (the accessibility hierarchy, Ariel, 1988; and the givenness hierarchy, Gundel et al., 1993) which reflect the fact that speakers choose less explicit referring expressions (e.g., pronouns), as they assume higher accessibility of the referent by the addressee as the discourse unfolds. While reduction of referring expressions show a difference between Introductions, Reintroductions and Maintenance in spoken (Tily & Piantadosi, 2009) and signed languages (Hoetjes et al., 2014; Perniss et al., 2015), not all studies show the same pattern. In Perniss and colleagues' study (2015), the authors compared the use of overt referring expressions between German Sign Language, Spoken German, and German co-speech gesture. Introductions were more overtly marked in terms of choice of referring expression than Reintroductions compared to Maintenance in all three, and Reintroductions were more overtly marked than Maintenance contexts in both German and German Sign Language. Therefore, explicitness of the referent reduced from Introduction > Reintroduction > Maintenance. However, in another study, Frederiksen and Mayberry (2016) analyzed reference tracking in four simple narratives produced by eight native American Sign Language (ASL) signers, and found no significant difference between maintained and reintroduced references. Similar to Frederiksen and Mayberry (2016), we find that there is no difference between the phonetic reduction of reintroduced signs and maintained signs. However, Frederiksen and Mayberry's study (2016) did not examine phonetic reduction.

Perhaps we should not expect a gradient decline in phonetic reduction between Introduction, Reintroduction and Maintenance, but rather a distinction between first mention and any subsequent mention (without a difference between Reintroduction and Maintenance). A subsequent mention in discourse can refer to at least two different things: repeating the same referent (in terms of Introduction vs. Reintroduction) or repeating the same lexical item (Lam & Watson, 2014). In studies like Frederiksen and Mayberry's (2016), these forms may be distinct – for example, "Charlie" when first introduced vs. 'he' when reintroduced, compared to repeating the lexical item "Charlie". In our study, however, these two forms of subsequent mention are conflated; in other words, a repetition of Charlie Chaplin is both a character repetition and a lexical repetition. In their study, Lam and Watson (2014) teased apart these two factors in spoken language, referent repetition and lexical repetition, using an innovative event description task. Their results revealed that lexical repetition showed the strongest reduction with a reduction in both duration and intensity, even in the absence of referent repetition. Overall, referent rep-

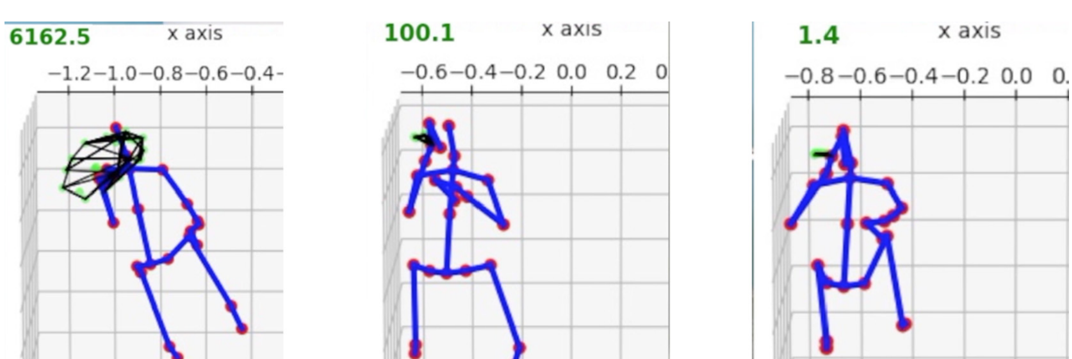

Fig. 8. An example of the volume (the black cage) for the sign CHARLIE-CHAPLIN in different referent status conditions, Introduction = 6161cm^3, Reintroduction = 100cm^3, Maintenance = 1.4cm^3.

etition led to less reduction – more specifically, reduction was observed in terms of intensity and not duration. In the results of the current study, we found a trend that maintained references were shorter in distance and smaller in volume than reintroduced references, but this was not found to be statistically significant. Further studies are necessary in order to tease apart these two different forms of repetition to determine whether similar patterns are found in signed languages.

Conclusions

The findings show that the use of 3D motion capture technologies, such as Microsoft Kinect, can be implemented successfully in the automatic measurement of movement parameters like those involved in phonetic reduction. A number of recent studies have adapted the use of motion capture for the coding of sign or gesture movement for various functions, including tracking of head movements (Puupponen, 2018), conventionalization of gestures (Namboodiripad et al., 2016) and in studies on the contribution of the body in indexing gender and sexuality (Stamp et al., submitted). Our study further promotes the use of technology for automatic coding of human motion data as an important step forward in the field of sign language linguistics. We note, however, that the Kinect cameras have recently been discontinued as new technology is being developed to track human body motion based on standard video cameras (e.g. Openpose, Mediapipe, etc.) (Cao et al., 2017; Lugaresi et al., 2019). As the depth information estimated by these newer, still experimental methods were not very accurate at the time of data collection, we opted to use a depth camera (Kinect) for our tracking.

We addressed three research questions in our exploration of phonetic reduction of repeated referring expressions in a young sign language, ISL. First, we found a clear difference in the degree of reduction based on referent status in a young sign language, with more reduction as predictability increases. Second, we provided evidence for the phonetic reduction by demonstrating which specific kinematic aspects of the signal are reduced. This study was able to objectively highlight the kinematic features which undergo phonetic reduction, namely, duration, distance covered, variance and volume, adding to previous studies (Tyrone & Mauk, 2010, 2012). Future studies are necessary to consider other processes, including movement deletion, and reduction in terms of handshape and location. Finally, we asked whether other articulators (i.e., head and torso) are involved in phonetic reduction, as a result of signalling discourse context. To this end, we tracked head and torso movements, and found that their action indeed reduces for predictable information, showing that they also play a key role in signaling discourse context. Since these articulators have rarely been tracked in previous reduction studies, our findings are expected to be useful for future studies related to phonetic reduction and information structure in language.

Data Statement

The data from this study is confidential and has not been made openly available. However, we provide the python code for extracting Kinect V2 features through the Open Science Framework (OSF) website: https://osf.io/bn5mg/.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Rose Stamp: Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Svetlana Dachkovsky:** Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Hagit Hel-Or:** Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Visualization, Writing – review & editing. **David Cohn:** Data curation, Formal analysis, Investigation, Methodology, Software, Writing – review & editing. **Wendy Sandler:** Conceptualization, Funding acquisition, Resources, Writing – review & editing.

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