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Lending a hand to signed language acquisition: Enactment and iconicity enhance sign recall in hearing adult American Sign Language learners

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For hearing adults, signed language processing increases the salience of iconicity and motor system involvement relative to spoken language processing. Nevertheless, it is unclear how embodied action, mental imagery and iconicity influence their acquisition of signed language. The current study examines the impact of these factors on sign acquisition by manipulating how signs are learned, as well as their semantic and phonological relatedness. The results of Experiment 1 demonstrated that American Sign Language (ASL) signs are learned more effectively via enactment than via referent visualisation and meaningless hand motion, and that iconic signs are learned more effectively than other types of signs. The results of Experiment 2 demonstrate that, when learned via enactment, semantically related ASL signs are recalled more accurately than phonologically related ASL signs. These results indicate that hearing adults' sign language acquisition can be enhanced via a learning method that combines mental imagery and meaningful embodied action (i.e., enactment), strengthening connections between the forms of signs and their referents.

Keywords: American Sign Language; Embodied cognition; Lexical organisation; Mental imagery; Sign acquisition.

Unlike spoken languages, which are articulated primarily via the vocal tract, signed language is produced primarily with the arms and hands. Due to the manner in which it is articulated, signed language comprises a broader range of muscle movements than spoken language, which may increase the salience of motor system involvement in its production for novice signers. Moreover, signed language is generally more iconic—representative of its referents—than spoken language. Unlike spoken language, signed language is naturally produced in the visual modality, which is more

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conducive to sign-to-referent mapping than the aural modality because more concepts can be represented visually than acoustically (Van der Hulst & Mills, 1996). The prominence of the motor system and iconicity in signed language processing suggest that embodied action—action enacted through body movements—and mental imagery—imagery generated via visualisation in the mind's eye—may play important roles in the processing of signed language, particularly in the initial stages of its acquisition as a second language (L2) by adults. The objective of the current study is to investigate whether active engagement in embodied action and mental imagery can enhance sign learning by adult English speakers unfamiliar with American Sign Language (ASL). To achieve this goal, this work examined adult English speakers' recollection of ASL signs varying in iconicity, as well as in semantic and phonological similarity that were learned via the generation of mental imagery and embodied action. The results elucidate the roles of embodied action and mental imagery in the initial stages of sign learning, providing insight into the similarity and distinctiveness of the cognitive mechanisms subserving signed and spoken adult L2 acquisition.

Although signed and spoken languages may seem quite different on the surface due to the modalities in which they are produced and comprehended, these languages are learned and processed using similar cognitive and neural mechanisms. Deaf children who learn signed language from birth reach milestones such as babbling, word order acquisition and wh-question production at the same time as hearing children who learn spoken language from birth (Lillo-Martin, 2000; Petitto, Holowka, Sergio, & Ostry, 2001; Pichler, 2001). Moreover, similar brain regions, including the left inferior frontal cortex, superior temporal cortex and planum temporale, are used to comprehend signed and spoken language, despite the fact that initial processing occurs in distinct regions for each language modality (primary and secondary visual and auditory cortices for speech; posterior occipoto-temporal regions for signed language; Corina, Vaid, & Bellugi, 1992; Emmorey et al., 2003; MacSweeney, Woll, Campbell, McGuire, et al., 2002; Petitto et al., 2000). Nevertheless, topographical constructions in signed language, in which real-world spatial relationships are reflected in sign space, recruit distinct brain regions (left inferior and superior parietal lobules and inferior temporal cortex) in which no activation has been observed during the processing of spoken language translations of these constructions (Emmorey et al., 2002; MacSweeney, Woll, Campbell, Calvert, et al., 2002). Some forms of both signed and spoken languages convey meaning iconically, facilitating their learnability and processing (Perniss, Thompson, & Vigliocco, 2010). For example, many spoken languages contain lexical items that represent their referents through sound symbolism, known as ideophones (Childs, 1994; Watson, 2001), and many signed languages contain signs that represent their referents visually through their form and motion (Frishberg, 1975; Taub, 2001). Taken together, these findings demonstrate that signed and spoken languages are similar in structure and are processed similarly, despite superficial differences in modality and initial processing.

Traditionally, theories of language processing have assumed that representations of language are amodal, symbolic and analytical (Chomsky, 1965; Pinker, 1984). Originally, these assumptions were applied to signed languages to affirm their status as languages, rather than gestural systems (Klima & Bellugi, 1979; Lillo-Martin, 1991; Stokoe, 2005), and they are still used to distinguish between signed language and gesture, particularly for gestures produced by signers (Marshall, Atkinson, Smulovitch, Thacker, & Woll, 2004). On the contrary, embodied theories of cognition posit that the body plays a pivotal role in language comprehension, regardless of language modality (Gibbs, 2006; Wilson, 2002). Specifically, one version of embodied cognition, known as grounded cognition, posits that language interpreters access their perceptual memories of referents, engaging the visual, motor and other relevant sensory systems in the process (Barsalou, 1999, 2008). Research testing the implications of grounded cognition has demonstrated that brain regions involved in the performance of body actions are engaged when these actions are conveyed via spoken language (Decety et al., 1997; Hauk, Johnsrude, & Pulvermüller, 2004; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Martin, Wiggs, Ungerleider, & Haxby, 1996), and that there is processing interference during the perception of objects or actions incongruent with the meanings of concurrent utterances (Fischer & Zwaan, 2008; Glenberg & Kaschak, 2002; Kaschak et al., 2005; Pecher & Zwaan, 2005; Zwaan, 2003). Given that embodied theories of cognition are not specific to one modality of language processing, several researchers have applied them to signed language. For example, there is evidence that the phonology of some signs can convey meaning through visual isomorphism (Perniss et al., 2010;

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Pietrandrea, 2002; Sallandre & Cuxac, 2002; Taub, 2001). Moreover, work using a theoretical framework related to embodied cognition, known as conceptual blending, has demonstrated that signers use space metaphorically to convey meaning and structure in some constructions (Dudis, 2004; Liddell, 2003; Wilcox, 2000).

Perhaps the most obvious feature of language that supports embodied theories of language processing is iconicity, which can be defined as the isomorphism between the phonological forms of lexical units (i.e., words or signs) and the attributes of referents in the corresponding (visual or auditory) modality (Simone, 1995). Both signs and words vary in iconicity on a spectrum ranging from highly iconic concrete lexical units (e.g., the English word *meow*, which conveys the characteristic sound made by cats; the ASL sign TO-HAMMER, which consists of one fist making two downward strokes above the palm of the flattened other hand) to semi-iconic metaphorical lexical units (e.g., the English words *snort*, *snout* and *snooty*, which are all related to the nose; the ASL sign GOAL, which consists of moving one hand with index finger extended forward horizontally towards the tip of the index finger of the other hand, which is extended vertically) to highly arbitrary abstract lexical units (e.g., the English word *dream*; the ASL sign COLOR, which consists of placing the dominant hand in front of the mouth and wiggling all of the fingers except for the thumb; see Figure 1; O'Brien, 1999; Taub, 2001). While iconicity was originally proposed as a holistic semiotic characteristic (McNeill, 1985), some sign linguists believe that iconicity can be encoded analytically through attributes of sign phonology (Sandler, 1989). Perception of iconicity in signed and spoken language is subjective and can vary between individuals; indeed, native producers of these languages may not be consciously aware of it until it is pointed out. However, iconicity in signs is likely salient and uniform among novice sign learners, given that they are unused to processing sign language and can use mnemonic devices such as iconicity to recall signs more efficiently.

Figure 1. ASL signs and English translations used in Experiment 1. Outlined sections indicate iconicity classification.

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On a broader level, iconicity is a gradient feature in both spoken and signed language, such that words and signs exhibit it to varying degrees (Frishberg, 1975; O'Brien, 1999; Perniss et al., 2010; Thompson, 2011; Vinson, Cormier, Denmark, Schembri, & Vigliocco, 2008). Spoken languages vary with respect to the amount of iconicity in the lexicon, ranging from Indo-European languages, in which sound symbolism is relatively rare, to sub-Saharan African and Southeast Asian languages, in which a subset of words known as ideophones contain iconic morphophonological features (Childs, 1994; Watson, 2001). Despite this variability, signed languages are generally more iconic than spoken languages due to their visual nature, which is evident from the impact of iconicity on semantic classification of signs by native signers (Vigliocco, Vinson, Woolfe, Dye, & Woll, 2005). For speakers of low-iconicity spoken languages such as English, iconicity in signed language may be particularly salient due to the contrast between its scarcity in the native language and its commonality in the target language. Additionally, the relationship between the visual attributes of signs and their referents may be especially apparent to hearing speakers because of the novelty of processing language in the visual modality. Thus, the iconicity inherent in signed language may enhance sign-referent association in hearing adult English speakers, thereby facilitating sign learning in the initial stages of L2 signed language acquisition.

Lexical acquisition presents an informative test case for embodied theories of language processing because it is when the initial links between lexical items and referents are forged. Because lexical acquisition is the first step towards learning a language, embodiment holds the potential to facilitate it significantly, especially for language processed in a modality conducive to its effects (e.g., signed language). According to embodied theories of language processing, for lexical acquisition to be successful, perceptions of referents must be associated with acoustic phonological forms of words in a spoken language or the visuo-motoric phonological forms of signs in a signed language. When learning an unfamiliar L2, lexical acquisition can be enhanced via embodiment by facilitating processing within three stages: lexical entry, in which the formal features of words, such as orthography and pronunciation, are encoded; lemma mediation, in which lemma information from the corresponding native language word is copied onto the L2 lexical entry and mediates its use; and L2 integration, in which semantic, syntactic and morphological information is integrated into the lexical entry (Jiang, 2000). Considered in conjunction with this model of lexical acquisition, embodied theories of language processing suggest that processing in the lexical entry stage may be facilitated through iconicity, and that it may be facilitated through mental simulation via mental imagery (i.e., images visualised in the mind's eye) and embodied action (i.e., movements enacted via the body) in the lemma mediation and L2 integration stages. Thus, according to embodied theories of language processing, iconicity, mental imagery and embodied action all play important roles in L2 lexical acquisition, regardless of language modality.

Although the semiotic relationships between iconic signs and their referents may seem transparent, there is evidence that the ability to recognise—and take advantage of—iconicity in signed language acquisition has a developmental trajectory. Hearing children are unable to reliably recognise the resemblance between iconic gestures and their referents until at least 26 months of age (Namy, 2008), and the facilitatory effect of iconic gestures on word learning increases between the ages of 2 and 4 (Gogate, Bahrick, & Watson, 2000; Marentette & Nicoladis, 2011). This developmental trajectory applies to sign recognition as well; while hearing 2.5-year-old children's recognition of iconic sign referents is at chance, hearing children aged 3–5 can reliably identify the referents of iconic signs (Tolar, Lederberg, Gokhale, & Tomasello, 2008). By age 10, hearing children unfamiliar with signed language can identify the referents of iconic signs as reliably as their deaf counterparts fluent in signed language (Ormel, Hermans, Knoors, & Verhoeven, 2009). The impact of iconicity on deaf children's sign acquisition is a matter of continued debate, with some work indicating that most of their first signs are iconic (Thompson, Vinson, Woll, & Vigliocco, 2012; Vinson et al., 2008), and other work indicating that they are not (Orlansky & Bonvillian, 1984). However, given a more inclusive definition of iconicity, the results of the latter study can also be interpreted as evidence that most of the first signs produced by deaf children are indeed iconic (Lloyd, Loeding, & Doherty, 1985). Moreover, there is evidence that deaf adult native signers who began learning signed language prior to 5 years of age process iconic signs more quickly than hearing individuals who began learning signed language after age 16, even though the latter group had been signing for 8 or more years

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(Thompson, Vinson, & Vigliocco, 2009). Finally, there is evidence that hearing adults unfamiliar with signed languages, as well as hearing adult novice signed language learners, recognise the referents of iconic signs more quickly (Campbell, Martin, & White, 1992) and can translate them more accurately (Baus, Carreiras, & Emmorey, 2012) than non-iconic signs. Furthermore, there is evidence that non-iconic sign recall by hearing adults unfamiliar with signed language decreases significantly as study–test intervals increase (Lieberth & Gamble, 1991), whereas no such patterns are found in native signers. Taken together, these findings indicate that once the ability to recognise iconicity develops, it can enhance L2 sign acquisition in hearing adults, as well as in deaf children and adults.

In addition to iconicity, mental imagery also plays an important role in lexical acquisition in signed and spoken languages. One line of research demonstrating the importance of mental imagery in L2 lexical acquisition focuses on the keyword method, in which learners are directed to choose a word from their native language that is phonologically similar to the target word, and then to formulate a mental image of the referents of the target word and the phonologically similar word interacting (Atkinson, 1975). There is evidence that this method promotes L2 lexical acquisition more effectively than verbal association of target words and their translations (Atkinson & Raugh, 1975; Raugh & Atkinson, 1975), and that it is particularly effective for highly imageable words, due to its basis in mental imagery (Ellis & Beaton, 1993). Another line of work indicates that both children and adults recall the meanings of words learned with accompanying gestures depicting their referents better than words learned without such gestures (Gogate et al., 2000; Gullberg, Roberts, & Dimroth, 2012; Kelly, McDevitt, & Esch, 2009; Macedonia, Müller, & Friederici, 2010; Morett, 2014; Tellier, 2008). These findings are consistent with embodied theories of language processing because they provide evidence that mental images of referents are accessed during lexical acquisition. Moreover, they support the dual coding theory of cognitive processing (Paivio, 1990), which posits that long-term memory encoding can be enhanced via simultaneous processing of visual and verbal information.

In addition to mental imagery and iconicity, embodied theories of language processing are consistent with the assumption that embodied action plays an important role in lexical acquisition in childhood and adulthood. Most work supporting these theories demonstrates that body motion depicting the affordances (i.e., action possibilities) of referents facilitates formation of the phonological-semantic associations crucial to word learning by enriching mental simulations of referents. For example, the enactment of gestures depicting word referents has been shown to enhance word learning in both childhood (Tellier, 2008) and adulthood (Morett, MacWhinney, & Gibbs, 2012), as well as word recall (Frick-Horbury, 2002), over the viewing of images or gestures. In early childhood, gesture production predicts vocabulary development (Rowe & Goldin-Meadow, 2009a, 2009b; Rowe, Özçalışkan, & Goldin-Meadow, 2008), and the transition to two-word speech is accompanied by gesture production (Capirci, Iverson, Pizzuto, & Volterra, 1996). In adulthood, there is evidence that prompted re-enactment of full body motions depicting actions (e.g., running, climbing) facilitates L2 word learning relative to methods that do not engage the motor system, such as oral repetition (Asher, 1969, 1972; Asher, Kusudo, & de la Torre, 1974). These findings indicate that embodied action contributes to lexical acquisition independently of iconicity and mental imagery. Evidence that embodied action facilitates lexical acquisition comes from research demonstrating that the onset of babbling in infancy is accompanied by repetitive motor movements (Iverson & Fagan, 2004), that restriction of hand movements by adults hinders lexical access (Frick-Horbury & Guttentag, 1998), and that beat (simple rhythmic) gesture enactment by adults improves lexical recollection (Lucero, Zaharchuk, & Casasanto, 2014). Given that the movements enacted in these last few studies were generally simple and repetitive and did not represent referents through their form, these findings demonstrate that embodied action is independent of mental imagery and iconicity, serving as a distinct semantic cue contributing to the formation of lexical representations even when iconicity is not present or recognisable.

Aside from embodied action, the motor system contributes to adult L2 acquisition through articulation. In order to produce spoken and signed language, the articulators (tongue and vocal muscles or hands and arms, respectively) must be moved in a pattern that produces sounds or motions comprising recognisable words or signs. Although there is disagreement regarding the role of the articulators in language comprehension, one major theory of speech perception—the motor

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theory—posits that listeners mentally simulate the motions necessary to produce speech in order to interpret it (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman & Mattingly, 1985). Evidence supporting this theory is derived from research showing that mirror neurons that fire when performing actions also fire when viewing them (Rizzolatti & Craighero, 2004) or hearing sounds that they produce (Kohler et al., 2002), and, more specifically, from research demonstrating that vocal articulator muscles are activated when speech is heard (Fadiga, Craighero, Buccino, & Rizzolatti, 2002; Watkins, Strafella, & Paus, 2003). More recently, however, it has been proposed that language is processed in parallel via a dorsal stream, which maps speech sounds onto articulatory-based representations, and a ventral stream, which maps speech sounds onto meaning (Hickok & Poeppel, 2004, 2007). Despite differences in the specifics of these theories, they both suggest that imitation of actions necessary to produce language may facilitate the acquisition of its phonological forms (i.e., words or signs) by hearing adults. Neuropsychological and functional neuroimaging evidence indicates that native signers do not show activation in fronto-parietal regions believed to subserve the mirror neuron system (Corina & Knapp, 2006; Emmorey, Xu, Gannon, Goldin-Meadow, & Braun, 2010). However, this work indicates that parietal brain regions involved in sign comprehension may also be active during sign production (Corina & Knapp, 2006), and that fronto-temporal regions of the mirror neuron system are active in hearing non-signers while viewing signs (Emmorey et al., 2010). Considered as a whole, this work indicates that sign production and comprehension may be more tightly linked than speech production and comprehension, particularly for individuals unfamiliar with signed language. As such, it is compatible with the claim that the body participates actively in language processing. By examining how iconicity, mental imagery and embodied action independently contribute to L2 sign acquisition in hearing adults unfamiliar with signed language, the current study provides insight into the impact of each of these factors on the initial formation of sign representations, clarifying how theories of embodied language processing apply to sign learning in this population.

In order to understand how iconicity, mental imagery and embodied action contribute to representations of signs formed in L2 sign acquisition, it is necessary to understand how these factors interact with sign phonology and semantics. In signed language, phonology comprises three or four visible parameters: handshape, movement, location, and, according to some researchers, orientation (Brentari, 1998; Liddell & Johnson, 1989; Stokoe, 2005). Semantics, on the other hand, consists of the conceptual relationships between referents (O'Grady, Dobrovolsky, & Aronoff, 2000). Thus, phonology is dependent upon modality of expression (signed vs. spoken language), whereas semantics is modality independent. Phonology, which is acquired via recognition of the visual characteristics of signs, and semantics, which is acquired via sign-referent association, interact with one another, affecting how signs are represented and organised in the mind. In support of this point, there is evidence that the influence of phonology on sign representation differs as a function of age of exposure to signed and spoken language. In sign monitoring tasks, non-native signers commit more phonological errors than native signers, whereas native signers commit more semantic errors than non-native signers (Mayberry & Fischer, 1989). Moreover, phonological relatedness facilitates sign recognition among native signers who learned signed language early, whereas both early and late sign learners benefit from semantic relatedness (Mayberry & Witcher, 2005). In sign lexical decision tasks, native signers demonstrate greater sensitivity to phonological similarity between signs and pseudo-signs than non-native signers (Gutiérrez, Müller, Baus, & Carreiras, 2012), and native signers' representations of signs can be primed by phonologically related signs, whereas no such effect is observed in non-native signers (Dye & Shih, 2006). Finally, there is evidence that experience with signed language influences similarity judgements for signs with several phonological parameters in common (Hildebrandt & Corina, 2002). Considered as a whole, these results indicate that non-native signers' phonological representations of signs are not as well articulated as those of native signers, resulting in greater confusion between signs that are phonologically—and therefore visually—similar in non-native signers.

In regard to sign semantics, there is evidence that once sign-meaning associations are initially formed, the semantic relationships between signs are relatively transparent to L2 signed language learners, non-native signers and native signers alike. Relative to modality-independent semantics, modality-dependent sign phonology is more challenging to learn; thus, signed language learners

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likely devote more attention to it. In support of this point, there is evidence that L2 sign learners can monitor sign handshape and location just as accurately as native signers, but cannot recognise sign meanings as accurately as native signers (Morford & Carlson, 2011). Similarly, phonological similarity affects both native and non-native signers' sign recognition, but semantic sign familiarity only affects non-native signers' sign recognition (Carreiras, Gutiérrez-Sigut, Baquero, & Corina, 2008). Moreover, there is evidence that L2 sign learners are better able to discriminate between signs with handshapes closer to a handshape category prototype than native signers (Morford, Grieve-Smith, MacFarlane, Staley, & Waters, 2008). In general, all of these results suggest that novice sign learners encounter greater difficulty learning phonologically similar signs than semantically similar signs because their sign representations are organised primarily by visual similarity rather than semantic similarity. Thus, novice L2 sign learners should be more likely to confuse visually similar, phonologically related signs than visually dissimilar, semantically related signs, resulting in more accurate recall of semantically related signs.

The current study seeks to elucidate the contributions of mental imagery and embodied action to hearing adult learners' L2 sign learning. In particular, it is designed to answer two research questions: (1) Can active engagement of mental imagery and/or embodied action facilitate adult L2 sign acquisition? (2) How does semantic and phonological relatedness of signs influence the impact of these factors? In Experiment 1, research question (1) was addressed by manipulating the method by which hearing adults learned signs, as well as the iconicity of target signs. In Experiment 2, research question (2) was addressed by manipulating the semantic and phonological relatedness of target signs learned via enactment. By virtue of their design, these studies illuminate the contributions of mental imagery and embodied action to adult L2 sign learning, providing insight into the cognitive mechanisms supporting signed language acquisition in this population.

EXPERIMENT 1: THE ROLES OF EMBODIED ACTION AND MENTAL IMAGERY

In the first experiment, the roles of embodied action and mental imagery in L2 sign lexical acquisition were examined. In order to determine the influence of these factors on sign acquisition, we manipulated how signs were learned, as well as the iconicity of signs. Participants learned signs via one of four methods in a 2 × 2 design in which embodied action and mental imagery were varied: enactment (+embodied action, +mental imagery), visualisation (–embodied action, +mental imagery), hand motion (+embodied action, –mental imagery) or sign viewing (–embodied action, –mental imagery). Signs also were classifiable as iconic, metaphorical or arbitrary based on ratings and semantic guessability by other hearing English speakers unfamiliar with ASL (O'Brien, 1999; see Materials section later). Based on the findings of previous research on spoken and sign language acquisition, we predicted that enactment, which taps into both embodied action and mental imagery, would facilitate sign acquisition and recall. Additionally, based on the findings of research indicating that iconicity enhances sign learning (Campbell et al., 1992; Lieberth & Gamble, 1991; Thompson et al., 2012) and that the iconicity of metaphorical signs is apparent to hearing English speakers unfamiliar with ASL (O'Brien, 1999), it was predicted that that iconic and metaphorical signs would be learned and recalled more effectively than arbitrary signs. Thus, overall, we predicted that active engagement of meaningful embodied action and mental imagery via enactment would facilitate sign learning in hearing individuals unfamiliar with ASL, particularly for iconic and metaphorical signs.

Methods

Participants. Twenty-six undergraduate students (8 males, 18 females; age mean: 19.76; *SD*: 2.94) at a medium-sized public university in the midwestern USA participated in return for partial course credit. Two of these participants were left-handed, and all participants had normal hearing and normal or corrected-to-normal vision. All participants were fluent English speakers and had no knowledge of ASL prior to the experiment. Seven participants reported bilingualism in a language other than English, with Spanish representing the most popular L2 (three participants), followed by Mandarin (two participants), Portuguese (one participant) and Shona (one participant). Of the remaining participants, 17 had learned at least one language other than English. Non-bilingual participants averaged 3.82 years of study (*SD* = 1.68),

TABLE 1
Age and L2 experience of participants in Experiment 1

	Range	*Mean (SD)*
Age	18–29	19.77 (2.94)
No. of L2s spoken	0–3	1.23 (0.71)
L2 years spoken	0–26	6.21 (6.41)

with Spanish representing the most popular L2 (13 participants), followed by French (4 participants), German (3 participants), Mandarin (1 participant) and Greek (1 participant; see Table 1).

Materials. Twenty ASL signs and their English translations were used in this research (see Figure 1). These signs were chosen as the best representatives of their categories—iconic, metaphorical or arbitrary—based on ratings and semantic guessability from other hearing English speakers from a previous study (O'Brien, 1999).[1] Iconic signs depicted concrete attributes of a concrete referent, and, according to ratings from English speakers, made the most sense, were the most natural, and had the most obvious meanings of all signs. An example of an iconic sign used in this study is TO-HAMMER, which is articulated by forming the dominant hand into a fist and producing two downward strokes over the non-dominant hand, which remains flat with the palm up.[2] Metaphorical signs depicted concrete attributes that are associated with a referent metaphorically, received intermediate ratings of sense-making, naturalness and obviousness, and had more guessable meanings than arbitrary signs. An example of a metaphorical sign used in this study is GOAL, which is articulated by moving one hand with index finger extended forward horizontally towards the tip of the index finger of the other hand, which is extended vertically. Arbitrary signs depicted attributes unrelated to a referent, had the lowest ratings of sense-making, naturalness and obviousness, and had the least guessable meanings. An example of an arbitrary sign used in this study is COLOR, which is articulated by placing the fingers of the dominant hand in front of the mouth and wiggling all of them except for the thumb back and forth. All signs were distinct from one another in form-related attributes, including handshape, articulation and orientation.

Videos shown during the learning phase of the experiment were created by recording a fluent female signer producing each sign.[3] Videos were clipped to 0.1 s before and after hand movements (average duration: 3.4 s), and sound tracks were removed.

Audio recordings of English translations of signs consisted of female synthesised speech generated by Natural Reader (Natural Soft, Ltd., 2012). Recordings were clipped to 0.1 s before and after speech (average duration: 1 s).

Procedure. The initial session of this study consisted of two phases: a learning phase and a test phase. In both phases, participants were instructed to keep their index fingers on the response buttons unless they were explicitly instructed to perform a motion in order to ensure that their hands remained still when necessary. In each learning trial, participants viewed a video of a randomly selected sign, and, following a 2,000 ms interstimulus interval, heard an audio recording of its English translation. After another 2,000 ms interval, this sequence of video and audio stimuli was repeated using the same sign. Following this, participants received instructions for actions to perform in accordance with the experimental condition to which a given sign was assigned in a within-subjects design (see later). After performing the actions specified in the instructions, participants pressed a button to proceed to the next learning trial. In order to provide sufficient opportunity for sign learning, all 20 learning trials were presented in three blocks (each trial presented once per block, yielding a total of 60 trials), with each sign assigned to the same condition across blocks for a given participant. The learning conditions to which signs of different types were presented were counterbalanced across participants, such that arbitrary signs were presented 25 times in each condition across participants, and that iconic and metaphorical signs were presented

[1] Unequal numbers of arbitrary (4), iconic (8) and metaphorical (8) signs were included because we were interested in exploring possible differences in sign learning as a function of grammatical class (noun vs. verb) in the latter two categories. No such differences were found, however.

[2] It was discovered following data collection that the model's pronunciation of at least two signs (TO-HAMMER and MESSAGE) was incorrect. Because participants were unfamiliar with ASL, the accuracy of their pronunciation of all signs was assessed against the model's pronunciation.

[3] This signer is the daughter of a deaf father who communicates via ASL, and she serves as an ASL interpreter at major events multiple times per year.

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50 times in each condition across participants. After completing the learning phase, participants received a 5-min break before continuing to the testing phase.

For signs assigned to the enactment condition, participants were instructed to re-enact the sign that they had just learned as accurately as possible using their own hands. This condition was designed to elicit mental imagery from participants through the visualisation of sign referents, as well as embodied action through the motor movements inherent in signing. For signs assigned to the hand motion condition, participants placed the thumb and upper four fingers of their dominant hand together and mimicked touching four dots configured in a square in a specified order, resulting in a punctuated x-shaped motion. This motion was verbally explained and demonstrated by the experimenter prior to the beginning of the experiment and was represented by a diagram displayed when participants were instructed to perform it. It was devised to be similar in complexity of form and motion to the signs learned in this experiment in order to provide a suitable control for movement, yet dissimilar in its combination of these attributes from any of the individual signs learned to avoid item-specific conflation. Thus, this condition was designed to elicit embodied action from participants through the motor movements necessary to produce the motion, but to avoid eliciting mental imagery due to its meaninglessness and the prompting that participants received upon the cue to produce it. For signs assigned to the visualisation condition, participants were instructed to close their eyes and formulate a mental image of a sign's meaning in their mind's eye. Participants were instructed to visualise sign meanings unrelated to the phonological forms of signs to avoid conflation with sign iconicity, given that mental images related to the phonological forms of signs would likely lead to an advantage for more iconic signs. This condition was designed to elicit mental imagery through explicit instruction to visualise sign referents, but to avoid eliciting embodied action by ensuring that participants' hands remained still, in accordance with the default instructions. In the sign viewing condition, the video of each sign and the audio recording of its translation were repeated one additional time to control for the elicited sign repetition in the enactment and visualisation conditions. This condition was designed to avoid eliciting mental imagery through its omission of explicit instructions to visualise signs or their referents, as well as tasks requiring implicit visualisation of signs or their referents. For each condition, the actions described earlier constitute one trial.

Following the 5-min break, participants proceeded to the testing phase. In each test trial, upon hearing the English translation of an ASL sign that they had learned, participants were instructed to produce the corresponding sign with their own hands as accurately as possible. If they were unable to remember the sign corresponding to a particular translation, participants were instructed to say "skip". After having produced each sign or saying "skip", participants pressed a button to proceed to the next trial. Participants' hand movements were video recorded during test trials for subsequent analysis. After all 20 translations had been presented, participants were dismissed.

To assess long-term sign recall, participants returned 1 week and 4 weeks after the first experimental session for two follow-up sessions. These sessions consisted of only the test block, which was identical to that of the first experimental session. Participants' hand movements were also video recorded during test trials of these follow-up sessions for subsequent analysis.

Coding. Following testing sessions, videos of participants' hand movements were analysed in two ways: holistically, for sign recall and forgetting, and analytically, for sign production accuracy. These coding schemes were complementary in resolution; the holistic schemes yielded two gross measures of sign recall, similar to the measures used to gauge recall in many psycholinguistic studies of L2 word learning (e.g., Kelly et al., 2009; Macedonia et al., 2011; Morett, 2014),[4] whereas the analytical scheme yielded a fine-grained measure of sign production accuracy, revealing important information about representations of learned signs.

Both the holistic sign recall and analytical sign production accuracy coding schemes were based on four phonological parameters of signed language: handshape, movement, location and orientation (Battison, 2003; Brentari, 1998). In both of these schemes, the following errors were coded as incorrect: errors in the shape of the hand used to produce the sign (handshape); errors in the articulation, or

[4] In this research, ASL signs were produced in response to English prompts (forward translation) rather than the more commonly used task of producing English words in response to signs (backwards translation) due to ceiling-level performance on the latter task in pilot testing.

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motion, of sign production (movement); errors in the locus of sign production in space (location); errors in the positioning of the hand(s) relative to each other (orientation). Given participants' unfamiliarity with ASL, these parameters were coded as incorrect only when they were notably deviant (e.g., fingers extended instead of curled; two strokes instead of three; neck-level instead of stomach-level placement; vertical instead of horizontal orientation). Signs produced using the non-dominant hand were not coded as incorrect for any of these phonological parameters because handedness is indistinct and pervasive in signed language L2 acquisition (Sandler, 1993).

In both holistic coding schemes, sign recall or forgetting was coded on a binary item-by-item basis. For sign recall, signs skipped or produced with at least one error in any phonological parameter were coded as *incorrect* (0), whereas signs produced without errors in any phonological parameter were coded as *correct* (1). Likewise, for sign forgetting, signs were coded either as *skipped* (0) or *attempted* (1). In the analytical sign production accuracy coding scheme, .25 was deducted for each incorrectly executed phonological parameter from a total possible score of 1 for each sign, given that four phonological parameters were used (see earlier). Thus, a sign produced with one incorrect parameter received a score of .75, and a sign produced with no correct parameters (including skipped signs) received a score of zero.

To determine reliability of coding, signs produced in the testing phase by seven randomly selected participants (27% of sample) were assessed by a secondary coder unaware of the experiment's design and hypotheses.[5] Using the coding schemes described earlier, the intraclass correlation coefficient (ICC) between the primary and secondary coders was .98 for sign recall, .99 for sign forgetting and .99 for sign production accuracy across learning–test intervals, indicating uniform application of the coding scheme and excellent interrater reliability.

Results

We first examined the effects of learning condition (enactment, visualisation, hand motion, sign viewing), learning–test interval (5 min, 1 week, 4 weeks) and sign iconicity (iconic, metaphorical, arbitrary) on sign recall.[6] This analysis revealed a main effect of learning–test interval, $F_1(2, 50) = 15.36, p < .001, \eta_p^2 = .38$; $F_2(2, 34) = 14.58, p < .001, \eta_p^2 = .46$, as well as a main effect of learning condition, $F_1(3, 75) = 4.85, p < .01, \eta_p^2 = .16$; $F_2(3, 51) = 4.82, p < .01, \eta_p^2 = .22$; see Figure 2.[7] Planned comparisons indicated that sign recall after 5 min was slightly more accurate than recall after 1 week ($p_1 = .06$; $p_2 = .07$) and a great deal more accurate than recall after 4 weeks ($p_1 < .001$; $p_2 < .001$), and that recall after 1 week was superior to recall after 4 weeks ($p_1 = .01$; $p_2 = .03$; see Table 2). Planned comparisons also indicated that enactment resulted in better sign recall than visualisation ($p_1 < .01$; $p_2 = .01$), and provided some evidence that it may have resulted in better sign recall than hand motion ($p_1 = .26$; $p_2 = .05$). No differences in sign recall under any of these conditions and the sign viewing condition were evident. No interaction was found between learning condition and learning–test interval, $F_1(6, 150) = 1.58, p = .16, \eta_p^2 = .06$; $F_2(6, 114) = 1.28, p = .28, \eta_p^2 = .06$. Iconicity did not affect sign recall; no differences in the recall of iconic, metaphorical and arbitrary signs were found ($F < 1$).

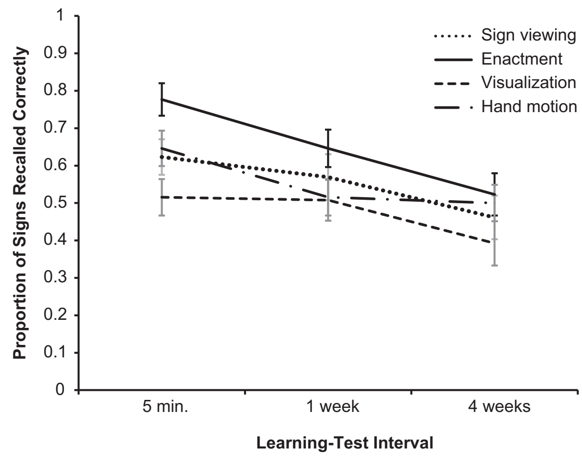

Figure 2. Sign recall in Experiment 1 by participant per learning condition and learning–test interval. Error bars represent standard error.

[5] Although the primary coder (L.M.M.) was aware of the experiment's design and hypotheses, she was blind to the learning conditions to which signs were assigned for specific participants during coding.

[6] To account for differences in the number of signs of each type, Bonferroni corrections were applied to alpha levels for tests examining the influence of sign iconicity.

[7] All values analysed using sign as a fixed factor in Experiment 1 are expressed proportionally due to unequal numbers of arbitrary, iconic and metaphorical signs, as well as unequal numbers of signs learned in each condition due to assignment across participants.

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TABLE 2
Mean sign recall in Experiment 1 by participant and sign per learning–test interval, learning condition and sign iconicity

Interval		*5 min*				*1 week*				*4 weeks*			
Analysis	*Condition/iconicity*	*SV*	*Enactment*	*Visualisation*	*HM*	*SV*	*Enactment*	*Visualisation*	*HM*	*SV*	*Enactment*	*Visualisation*	*HM*
By participant		3.12	3.88	2.58	3.23	2.85	3.23	2.54	2.58	2.31	2.62	1.96	2.5
		(1.21)	(1.11)	(1.24)	(1.21)	(1.57)	(1.27)	(1.39)	(1.24)	(1.49)	(1.44)	(1.51)	(1.24)
By sign	Arbitrary	0.58	0.80	0.55	0.69	0.63	0.65	0.48	0.66	0.63	0.65	0.27	0.40
		(.40)	(.16)	(.31)	(.22)	(.39)	(.23)	(.30)	(.16)	(.45)	(.10)	(.27)	(.25)
	Iconic	0.62	0.66	0.53	0.54	0.58	0.67	0.52	0.51	0.43	0.53	0.46	0.57
		(.26)	(.19)	(.18)	(.25)	(.27)	(.22)	(.20)	(.20)	(.27)	(.27)	(.11)	(.26)
	Metaphorical	0.73	0.88	0.49	0.66	0.59	0.66	0.54	0.38	0.49	0.45	0.41	0.39
		(.28)	(.19)	(.27)	(.28)	(.28)	(.15)	(.28)	(.26)	(.31)	(.27)	(.24)	(.29)

SV, sign viewing; HM, hand motion.

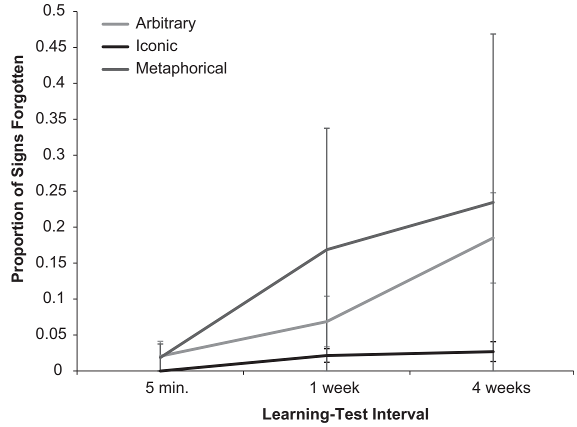

Figure 3. Proportion of signs forgotten in Experiment 1 by sign per iconicity and learning–test interval. Error bars represent standard error.

We next examined the effects of learning condition, learning–test interval and sign iconicity on sign forgetting. This analysis revealed a main effect of learning–test interval, $F_1(2, 50) = 24.87$, $p < .001$, $\eta_p^2 = .50$; $F_2(2, 34) = 40.18$, $p < .001$, $\eta_p^2 = .70$, as well as an interaction of learning–test interval and iconicity by sign, $F(4, 34) = 10.27$, $p < .001$, $\eta_p^2 = .55$; see Figure 3. A simple main effects analysis revealed that sign forgetting did not differ as a function of iconicity at 5 min, $F(2, 17) = 1.85$, $p = .19$, $\eta_p^2 = .18$, but it differed as a function of iconicity at 1 week, $F(2, 17) = 8.25$, $p < .01$, $\eta_p^2 = .49$, and 4 weeks, $F(2, 17) = 15.23$, $p < .001$, $\eta_p^2 = .64$. Planned comparisons revealed that more metaphorical signs than iconic signs were forgotten after 1 week ($p < .01$) and 4 weeks ($p < .001$), and that more arbitrary signs than iconic signs were forgotten after 4 weeks ($p = .01$; see Table 3). Similarly, sign forgetting differed as a function of learning–test interval for arbitrary signs, $F(2, 6) = 11.53$, $p < .01$, $\eta_p^2 = .79$, and metaphorical signs, $F(2, 14) = 28.44$, $p < .001$, $\eta_p^2 = .80$, and trended towards differing for iconic signs, $F(2, 14) = 3.15$, $p = .07$, $\eta_p^2 = .31$. More metaphorical signs were forgotten after 1 week ($p = .01$) and 4 weeks ($p < .001$) than 5 min, and slightly more metaphorical signs ($p = .06$) and arbitrary signs ($p = .09$) were forgotten after 4 weeks than 1 week, whereas no such differences were found for iconic signs.

Finally, we examined the effects of learning condition, learning–test interval and sign iconicity on sign production accuracy. The results revealed a main effect of learning–test interval, $F_1(2, 50) = 26.01$, $p < .001$, $\eta_p^2 = .51$; $F_2(2, 34) = 39.06$, $p < .001$,

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TABLE 3
Mean signs forgotten in Experiment 1 by participant and sign per learning–test interval, learning condition and sign iconicity

Interval		*5 min*				*1 week*				*4 weeks*			
Analysis	*Condition/iconicity*	*SV*	*Enactment*	*Visualisation*	*HM*	*SV*	*Enactment*	*Visualisation*	*HM*	*SV*	*Enactment*	*Visualisation*	*HM*
By participant		0.04	0.08	0.08	0.00	0.31	0.54	0.31	0.62	0.77	0.65	0.73	0.62
		(.20)	(.27)	(.39)	(.00)	(.55)	(.65)	(.55)	(.75)	(1.03)	(.80)	(.96)	(.80)
By sign	Arbitrary	0.00	0.08	0.00	0.00	0.03	0.13	0.07	0.05	0.10	0.21	0.18	0.25
		(.00)	(.17)	(.00)	(.00)	(.05)	(.16)	(.15)	(.10)	(.12)	(.09)	(.07)	(.29)
	Iconic	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.05	0.03	0.02	0.06	0.00
		(.00)	(.00)	(.00)	(.00)	(.00)	(.06)	(.05)	(.07)	(.09)	(.05)	(.08)	(.00)
	Metaphorical	0.01	0.02	0.05	0.00	0.11	0.20	0.11	0.26	0.25	0.21	0.24	0.23
		(.03)	(.05)	(.09)	(.00)	(.18)	(.13)	(.13)	(.20)	(.14)	(.20)	(.14)	(.19)

SV, sign viewing; HM, hand motion.

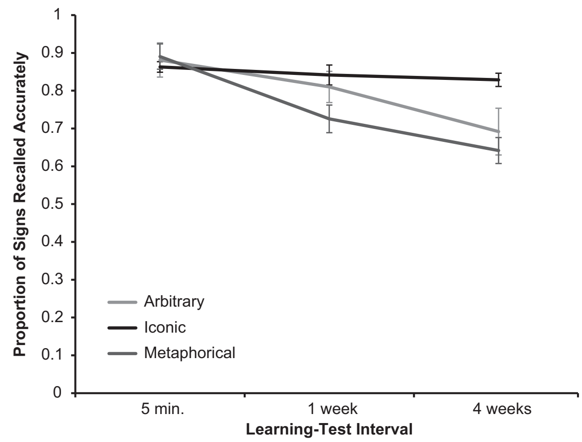

Figure 4. Proportion of signs produced accurately in Experiment 1 by sign per iconicity and learning–test interval. Error bars represent standard error.

$\eta_p^2 = .70$, whereas learning condition failed to reach significance, $F_1(3, 75) = 1.69$, $p = .18$, $\eta_p^2 = .06$; $F_2(3, 51) = 1.88$, $p = .15$, $\eta_p^2 = .09$. By sign, there was also a significant interaction of learning–test interval and iconicity, $F(4, 34) = 9.06$, $p < .001$, $\eta_p^2 = .52$; see Figure 4. A simple main effects analysis revealed that participants' sign production accuracy did not differ as a function of iconicity at 5 min, $F < 1$, but sign production accuracy differed as a function of iconicity at 1 week, $F(2, 17) = 3.54$, $p = .05$, $\eta_p^2 = .29$, and 4 weeks, $F(2, 17) = 9.61$, $p = .002$, $\eta_p^2 = .53$. Planned comparisons revealed that iconic signs were produced more accurately than metaphorical signs at 1 week ($p = .06$) and 4 weeks ($p = .001$), and that iconic signs were produced slightly more accurately than arbitrary signs at 4 weeks ($p = .06$; see Table 4). Similarly, sign production accuracy differed as a function of learning–test interval for arbitrary signs, $F(2, 6) = 25.96$, $p = .001$, $\eta_p^2 = .90$, and metaphorical signs, $F(2, 14) = 26.72$, $p < .001$, $\eta_p^2 = .80$, but not iconic signs, $F(2, 14) = 1.53$, $p = .25$, $\eta_p^2 = .18$. Metaphorical signs were produced more accurately after 5 min than 1 week ($p = .01$) and 4 weeks ($p = .001$), and after 4 weeks than 1 week ($p = .03$). Additionally, arbitrary signs were produced more accurately after 5 min than 4 weeks ($p = .02$); however, no such differences were observed for iconic signs.

Discussion

The results of Experiment 1 confirmed the prediction that enactment would enhance L2

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TABLE 4
Mean sign production accuracy in Experiment 1 by participant and sign per learning–test interval, learning condition and sign iconicity

Interval		*5 min*				*1 week*				*4 weeks*			
Analysis	*Condition/iconicity*	*SV*	*Enactment*	*Visualisation*	*HM*	*SV*	*Enactment*	*Visualisation*	*HM*	*SV*	*Enactment*	*Visualisation*	*HM*
By participant		4.32	4.60	4.19	4.48	4.03	4.02	3.90	3.82	3.66	3.79	3.48	3.65
		(.52)	(.47)	(.66)	(.43)	(.75)	(.81)	(.80)	(.83)	(1.10)	(0.94)	(1.01)	(.88)
By sign	Arbitrary	0.85	0.89	0.88	0.91	0.82	0.80	0.76	0.87	0.80	0.74	0.61	0.62
		(.15)	(.15)	(.10)	(.06)	(.17)	(.12)	(.12)	(.06)	(.24)	(.06)	(.15)	(.25)
	Iconic	0.86	0.90	0.84	0.85	0.86	0.87	0.82	0.81	0.84	0.83	0.81	0.84
		(.10)	(.08)	(.07)	(.08)	(.10)	(.09)	(.10)	(.10)	(.09)	(.09)	(.07)	(.08)
	Metaphorical	0.91	0.94	0.81	0.90	0.80	0.75	0.76	0.60	0.67	0.69	0.63	0.58
		(.11)	(.12)	(.15)	(.09)	(.18)	(.10)	(.15)	(.21)	(.17)	(.20)	(.15)	(.22)

SV, sign viewing; HM, hand motion.

ASL sign acquisition by adults unfamiliar with signed languages. Consistent with the prediction, enactment resulted in more accurate sign recall than referent visualisation and meaningless hand motion. In considering the effect of enactment alone, it is unclear whether its facilitation is due to participants' active engagement in both embodied action and mental imagery, or whether it is due to their engagement in embodied action (i.e., motor activity) alone. However, the lack of enhancement observed for signs learned with accompanying irrelevant hand motion suggests that the facilitatory effect of enactment is not due to embodied action alone. Considered in contrast to one another, these results demonstrate that motor activity must be related to the form and/or meaning of signs in order to facilitate acquisition; thus, embodied action must be linked to mental imagery for sign acquisition to be successful. Although it is unclear whether repetition of spoken words aloud facilitates their recall via production, research on the effect of subvocal (i.e., silent) repetition on word learning suggests that rehearsal of the conceptual meanings of words and the speech gestures necessary to produce them facilitates lexical acquisition, rather than the actual production of the speech gestures of these words (Baddeley, Gathercole, & Papagno, 1998; Gathercole, 2006; Gathercole, Hitch, Service, & Martin, 1997). In future work, "subvocal" rehearsal of signs could be compared to overt rehearsal to tease apart the effects of conceptual sign-meaning association and motoric sign production. The finding that enactment enhances sign recall is consistent with theories of embodied cognition because it indicates that the motor activity of sign enactment enriches the formation of mental representations of signs, allowing for more accurate sign recall and re-enactment. Moreover, the lack of enhancement observed for referent visualisation suggests that if mental imagery contributes to sign recall, it may only do so in conjunction with related embodied action via enactment. It is important to note that the effects of embodied action (i.e., motion) on sign acquisition relative to mental imagery may have been increased by testing recall via production. A stronger test of the predictions of theories of embodied could be obtained by assessing sign recall using a measure of comprehension as a dependent variable, given that sign recall via comprehension may depend more on mental imagery than sign recall via production.[8]

The findings concerning the role of mental imagery suggest that mental imagery must be related to sign forms in order to facilitate lexical acquisition among hearing adult L2 sign learners. As stated earlier, visualisation of sign referents unrelated to sign forms did not result in significantly better sign recall than meaningless hand motion or sign viewing. Thus, active engagement in mental imagery via visualisation of sign referents does not appear to enhance sign acquisition among adult learners unfamiliar with signed language. Signed language, unlike spoken language, is produced and comprehended via the visual modality; thus, creating mental images of referents may interfere with, rather than complement, the processing of signed language. Moreover, findings indicating that learners less familiar with signed language devote more attention to sign phonology highlight the importance of sign forms in the early stages of sign acquisition. In support of these points, sign iconicity reduced sign production errors and forgetting, such that fewer iconic signs were forgotten or were produced with errors after a delay of 1 or 4 weeks than metaphorical or arbitrary signs. This finding may be explained by the transparent representation of referents via the forms of these signs, which may facilitate their processing and acquisition, rather than hindering it, as referent visualisation did. Moreover, this finding is consistent with research indicating that iconic signs are more easily acquired by deaf children (Thompson et al., 2012) and are more easily associated with their referents by both deaf and hearing adults (Thompson, Vinson, & Vigliocco, 2010). Interestingly, no significant difference in sign production errors or forgetting was found between metaphorical and arbitrary signs. This result is inconsistent with previous work indicating that the meanings of these metaphorical ASL signs were guessed more accurately by individuals unfamiliar with signed language than the meanings of these arbitrary signs (O'Brien, 1999). Nevertheless, the more accurate production and decreased forgetting of iconic signs relative to arbitrary signs suggests that iconicity facilitates sign-referent association through the mapping of visual features of signs onto those of referents, indicating that mental imagery contributes to sign recall and production in individuals learning ASL signs for the first time.

While it is clear that enactment results in more robust sign representations than meaningless hand motion or referent visualisation, it is unclear exactly how elaborated the sign representations produced via enactment are. In particular, it is unclear whether sign representations produced via enactment are organised semantically, or if they are organised phonologically. Previous work suggests that semantically related signs may be easier for individuals unfamiliar with signed language to acquire because they are more readily differentiated on the basis of their visual characteristics than phonologically related signs, and because their referents are conceptually related (Mayberry & Fischer, 1989; Mayberry & Witcher, 2005). Given that the signs in Experiment 1 were all semantically or phonologically distinct from one another, it is impossible to discern the mental organisation of signs learned via enactment according to these factors from the results of this study. Experiment 2 addresses these issues by examining acquisition via enactment of semantically and phonologically related ASL signs by individuals unfamiliar with ASL. By doing so, Experiment 2 provides insight into the qualitative features of newly formed mental representations of signs learned via enactment during the initial stages of sign acquisition, as well as their mental representation in the minds of novice learners.

EXPERIMENT 2: PHONOLOGICAL AND SEMANTIC ORGANISATION

In the second experiment, we examined how representations of ASL signs created via enactment are organised in the initial stages of sign acquisition. In order to examine the mental organisation of newly formed sign representations, signs that were related either phonologically (in form) or semantically (in meaning) were learned. In this experiment, all signs were learned via enactment in order to control for—and maximise—the influences of mental imagery and embodied action, thereby facilitating the sign acquisition via these factors. It was predicted that adults previously unfamiliar with ASL would recollect semantically related signs better than phonologically related signs. Furthermore, it was predicted that these individuals would produce phonologically related signs with more errors in movement and

[8] This study originally tested sign recall via comprehension (i.e., asking participants to provide the English gloss for each sign) in addition to production. However, this measure was dropped due to ceiling effects in pilot testing.

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orientation than semantically related signs, given that these are the parameters that most often distinguished these phonologically related signs from one another. These predictions were based on work examining sign learning via comprehension suggesting that signs are organised according to visual similarity (i.e., phonologically) in non-native signers (Mayberry & Fischer, 1989; Mayberry & Witcher, 2005), as well the results of Experiment 1, which suggest that enactment highlights the meanings, as well as the forms, of signs.

Methods

Participants. Twenty-nine undergraduate students (7 males, 22 females; age mean: 18.38; age *SD*: 0.68) at a medium-sized public university in the midwestern US participated in return for partial course credit. Four of these participants were left-handed, and all participants had normal hearing and normal or corrected-to-normal vision. All participants were fluent English speakers and had no knowledge of ASL prior to the experiment. Six participants reported bilingualism in a language other than English, with Gujarati representing the most popular L2 (two participants), followed by Spanish (one participant), Swahili (one participant), Serbo-Croatian (one participant) and Mandarin (one participant). Of the remaining participants, 17 had learned at least one language other than English. Non-bilingual participants averaged 3.52 years of study (SD = 2.47), with Spanish representing the most popular L2 (10 participants), followed by French (3 participants), Latin (2 participants), German (1 participant) and Italian (1 participant; see Table 5).

Materials. Twenty-four ASL signs and their English glosses, divided into two classes of 12 semantically related and 12 phonologically related signs, were used in this research (see Figure 5). Semantically related signs were defined as signs with related meanings, whereas phonologically related signs were defined as signs with similar visual forms. Signs in each category were divided into four subgroups of three, classified by semantic or phonological relatedness. Signs meeting these criteria were initially chosen in consultation with a native English speaker fluent in ASL, who also served as the model in sign videos (see later).

To confirm the validity of these groups, the relationships between signs were assessed independently by eight English speakers unfamiliar with ASL who did not participate in this experiment. These individuals rated each sign in relation to every other sign for similarity in form, as well as the English meaning of each sign in relation to the English meaning of every other sign for similarity in meaning, on a 1 (*completely dissimilar/unrelated*)—7 (*extremely dissimilar-unrelated*) scale. These ratings confirmed that signs in the phonologically related class within each phonologically similar group were rated as more visually similar to each other than the average of all other signs in the phonologically related class (M_{Group} = 5.02, SD_{Group} = .62; M_{Other} = 2.89, SD_{Other} = .03), $t(3)$ = 6.55, p = .007, d = 4.85. However, signs in the semantically related class within each semantically similar group were not rated as more visually similar to one another than the average of all other semantically related signs (M_{Group} = 2.51, SD_{Group} = 1.65; M_{Other} = 1.73, SD_{Other} = .02), $t > 1$. Likewise, translations of signs in the semantically related class within each semantically similar group were rated as more similar in meaning than the average of all other translations of signs in the semantically related class (M_{Group} = 4.83, SD_{Group} = 1.13; M_{Other} = 1.79, SD_{Other} = .08), $t(3)$ = 5.33, p = .01, d = 3.76. However, the translations of signs in the phonologically related class within each phonologically similar group were not rated as more similar in meaning to one another than the average of all other phonologically related signs (M_{Group} = 1.64, SD_{Group} = .37; M_{Other} = 1.58, SD_{Other} = .02), $t > 1$.

Additionally, the same individuals subsequently rated the iconicity of all signs used in this experiment based on provided translations on a 1 (*form completely unrepresentative of meaning*)—7 (*form extremely representative of meaning*) scale. Semantically related signs were rated as more iconic than phonologically related signs (M_{Sem} = 3.77, SD_{Sem} = 1.69; M_{Phono} = 2.27, SD_{Phono} = 1.14), $t(22)$ = 2.55, p = .02, d = 1.04. In order to control for this difference, iconicity was used as a covariate in all analyses of sign recollection.

Videos shown during the learning phase of the experiment were created by recording a fluent

TABLE 5
Age and L2 experience of participants in Experiment 2

	Range	*Mean* (SD)
Age	18–29	19.22 (2.69)
No. of L2s spoken	0–2	0.86 (0.52)
L2 years spoken	0–18	6.03 (5.88)

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Figure 5. ASL signs and English translations used in Experiment 2. Outlined sections indicate phonological and semantic groups.

female ASL signer (different from the signer in Experiment 1) producing each sign.[9] Videos were clipped to 0.1 s before and after hand movements (average duration: 3.08 s), and soundtracks were removed.

Audio recordings of English translations of signs consisted of female synthesised speech generated by Natural Reader (Natural Soft, Ltd., 2012). Recordings were clipped to 0.1 s before and after speech (average duration: 1 s)

Procedure. The procedure of this experiment was similar to the procedure of Experiment 1, except that in all learning trials, participants were instructed to re-enact signs using their own hands, as in the enactment condition of Experiment 1. As in Experiment 1, order of sign presentation was randomised on a participant-by-participant basis, with semantically and phonologically related signs interleaved in the interest of reducing confusion of signs due to order of presentation. In this experiment, only one follow-up session to test long-term sign recall was held 1 week after the first experimental session. No 4-week follow-up session was held in this experiment due to the increased difficulty of the task as a result of the larger quantity of signs and the greater semantic and phonological relatedness of the signs relative to Experiment 1.

Coding. The holistic coding schemes utilised in this experiment for sign recall and forgetting were identical to the corresponding coding schemes utilised in Experiment 1. For the analytical coding scheme, in order to examine the influences of each of the four phonological parameters (movement, handshape, location, orientation), these parameters were entered as an independent variable in an additional level of analysis. In this scheme, each parameter was coded in a binary manner as

[9] This signer is currently studying to become a speech-language pathologist, and learned ASL beginning as an undergraduate as part of her training.

either *correctly produced* (1) or *incorrectly produced* (0), yielding a total score of 4 for each sign.

To determine reliability of coding, signs produced in the testing phase by eight randomly selected participants (28% of sample) were assessed by a secondary coder unaware of the experiment's design and hypotheses. Using the coding schemes referenced earlier, the ICC between the primary and secondary coders was .72 for sign recall, .98 for sign forgetting and .87 for sign production accuracy across learning–test intervals, indicating uniform application of the coding scheme and good to excellent interrater reliability.

Results

We first examined the impacts of learning–test interval (5 min, 1 week) and sign class (semantically related, phonologically related) on sign recall. This analysis revealed a main effect of learning–test interval, $F_1(1, 28) = 46.17$, $p < .001$, $\eta_p^2 = .46$; $F_2(1, 22) = 19.51$, $p < .001$, $\eta_p^2 = .48$, as well as a main effect of sign class by participant, $F_1(1, 28) = 23.79$, $p < .001$, $\eta_p^2 = .62$; $F_2(1, 22) = 1.29$, $p = .27$, $\eta_p^2 = .06$.[10] However, the interaction between sign class and learning–test interval failed to reach significance, $F_1 < 1$; $F_2 < 1$; see Figure 6. Planned comparisons indicated that sign recall at 5 min exceeded sign recall at 1 week ($p_1 < .001$; $p_2 < .001$), and that recall of semantically related signs was significantly more accurate than recall of phonologically related signs by participant ($p < .001$; see Table 6).

We next examined the impact of learning–test interval and sign class on sign forgetting. This analysis revealed a main effect of learning–test interval, $F_1(1, 28) = 39.45$, $p < .001$, $\eta_p^2 = .59$; $F_2(1, 22) = 20.89$, $p < .001$, $\eta_p^2 = .50$, as well as a marginal main effect of sign class by participant, $F_1(1, 28) = 3.97$, $p = .06$, $\eta_p^2 = .12$; $F_2 < 1$.[11] There was also a marginal interaction between learning–test interval and sign class by participant, $F_1(1, 28) = 2.01$, $p = .17$, $\eta_p^2 = .07$; $F_2(1, 22) = 3.96$, $p = .06$, $\eta_p^2 = .16$; see Figure 7. Planned comparisons indicated that more signs were forgotten after 1 week than 5 min

[10] Without including sign iconicity as a covariate, no significant difference was found for sign class by sign either, $F_2(1, 22) = 1.71$, $p = .20$, $\eta_p^2 = .07$.

[11] Without including sign iconicity as a covariate, no significant difference was found for sign class by sign either, $F_2 < 1$.

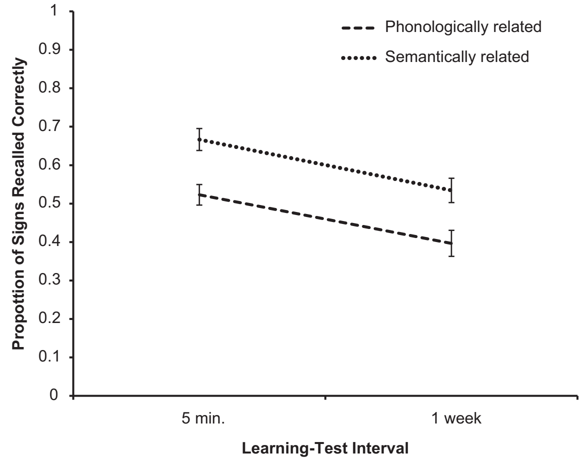

Figure 6. Sign recall in Experiment 2 by participant per sign class and learning–test interval. Error bars represent standard error.

($p_1 < .001$; $p_2 < .001$), and that more phonologically related signs were forgotten than semantically related signs ($p = .06$; see Table 7).

Finally, we examined the impacts of learning–test interval and sign class on sign production accuracy. The results revealed a main effect of learning-test interval, $F_1(1, 28) = 34.39$, $p < .001$, $\eta_p^2 = .55$; $F_2(1, 22) = 4.87$, $p < .001$, $\eta_p^2 = .67$. Planned comparisons indicated that signs were produced more accurately after 5 min than 1 week ($p_1 < .001$; $p_2 < .001$; see Table 8). The results also revealed a significant interaction of sign class and error type by participant, $F_1(3, 84) = 10.71$, $p < .001$, $\eta_p^2 = .28$; $F_2 < 1$.[12] A simple main effect analysis revealed that more phonologically related than semantically related signs were produced with movement errors, $t(28) = 2.81$, $p = .009$, $d = .48$, and orientation errors, $t(28) = 4.90$, $p < .001$, $d = 1.07$, but that no difference was found for handshape errors, $t(28) = 1.22$, $p = .23$, $d = .20$, or location errors, $t < 1$ (see Figure 8).

Discussion

The results of Experiment 2 confirmed the prediction that, for signs learned via enactment by hearing adults unfamiliar with ASL, semantically related signs would be recalled more accurately than phonologically related signs. In accordance with this prediction, participants correctly recalled

[12] Without including sign iconicity as a covariate, no significant difference was found for sign class by sign either, $F_2 < 1$.

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TABLE 6
Mean signs recalled in Experiment 2 by participant and sign per learning–test interval and sign class

Interval	*5 min*		*1 week*	
Condition/analysis	*Phonological*	*Semantic*	*Phonological*	*Semantic*
By participant	6.28 (1.73)	8.00 (1.85)	4.76 (2.20)	6.41 (2.04)
By sign	15.17 (7.77)	19.33 (7.16)	11.58 (6.82)	15.50 (8.92)

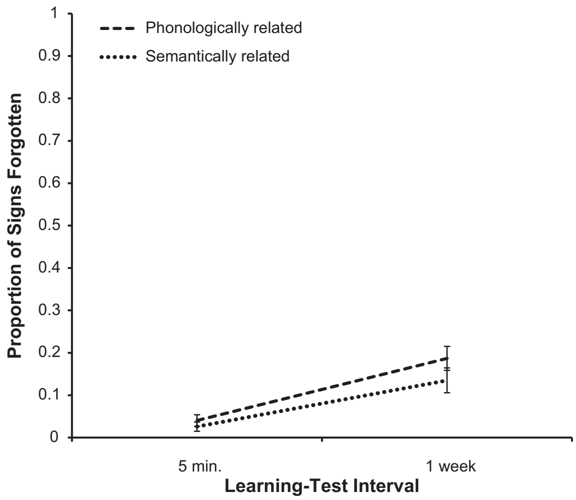

Figure 7. Sign forgetting in Experiment 2 by participant per learning condition and learning–test interval. Error bars represent standard error.

more semantically related signs than phonologically related signs after both 5 min and 1 week. Notably, this was the case even when iconicity was used as a covariate, indicating that this effect was not caused by the greater iconicity of semantically related signs. This result suggests that, when representations of signs are first formed via enactment in the minds of individuals unfamiliar with signed language, they are organised by visual similarity, which corresponds to sign phonology. The finding that individuals previously unfamiliar with ASL recall phonologically related ASL signs less accurately than semantically related ASL signs is consistent with previous work demonstrating that non-native signers are more likely to commit phonological errors than semantic errors when producing signs (Mayberry & Fischer, 1989; Mayberry & Witcher, 2005). This observation is also consistent with the results of Experiment 1, which indicate that enactment strengthens the form-meaning associations between signs and their referents, thereby facilitating sign acquisition. Thus, these results suggest that though sign representations are initially organised on the basis of visual similarity, enactment may enhance the semantic organisation of signs, which may facilitate progression to a more mature state of sign lexical organisation.

The results of the error analysis confirm these observations, and provide further evidence of how semantically and phonologically related ASL signs learned via enactment are represented in the minds of hearing adults previously unfamiliar with ASL. Consistent with our prediction, the error analysis demonstrated that participants committed more movement and orientation errors for phonologically related signs than for semantically related signs. This finding supports the prediction that participants would confuse phonologically related signs with one another more often than semantically related signs, given that most of signs within phonologically related groups differed from one another on the basis of these parameters, rather than on the basis of handshape or location. In general, errors committed by participants when producing signs confirm that, for novice L2 sign language learners, signs are organised on the basis

TABLE 7
Mean signs forgotten in Experiment 2 by participant and sign per learning–test interval and sign class

Interval	*5 min*		*1 week*	
Condition/analysis	*Phonological*	*Semantic*	*Phonological*	*Semantic*
By participant	0.48 (.87)	0.31 (.71)	2.24 (1.83)	1.62 (1.90)
By sign	1.17 (1.11)	0.75 (.97)	5.42 (3.58)	3.92 (3.00)

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TABLE 8
Mean sign production accuracy in Experiment 2 by participant and sign per learning–test interval, sign class and error type

	Interval	*5 min*		*1 week*	
Analysis	*Condition/error*	*Phonological*	*Semantic*	*Phonological*	*Semantic*
By participant	Movement	3.79 (1.82)	3.24 (1.38)	5.34 (2.13)	4.48 (2.32)
	Handshape	1.76 (2.03)	1.48 (1.48)	3.55 (2.35)	3.10 (2.09)
	Location	0.66 (1.01)	0.90 (1.05)	2.62 (1.93)	2.41 (2.04)
	Orientation	2.66 (1.70)	1.24 (0.99)	4.45 (1.94)	2.86 (1.96)
By sign	Movement	9.08 (7.14)	13.17 (7.59)	7.67 (5.99)	10.83 (7.12)
	Handshape	4.25 (2.56)	8.83 (4.13)	3.33 (3.50)	7.50 (4.89)
	Location	1.58 (1.68)	6.50 (3.85)	2.00 (3.10)	5.83 (4.41)
	Orientation	6.42 (4.74)	10.92 (6.61)	2.83 (4.17)	6.92 (6.20)

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of visual similarity, even when sign-meaning associations are strengthened through enactment.

Overall, the results of Experiment 2 provide insight into the qualitative features of newly formed sign representations acquired via enactment by hearing adults unfamiliar with signed language. On the one hand, the greater number of movement and orientation errors for phonologically related signs confirms the results of previous work demonstrating that signs are organised on the basis of visual similarity, which reflects sign phonology, in the initial stages of sign acquisition. On the other hand, the superior recall accuracy for semantically related signs provides evidence that enactment strengthens the associations between signs and their referents in novice learners, resulting in better semantic organisation in the early stages of sign acquisition. Taken together, these results suggest that enactment may provide hearing adults unfamiliar with signed language with a learning advantage, resulting in more articulated and robust initial representations of signs.

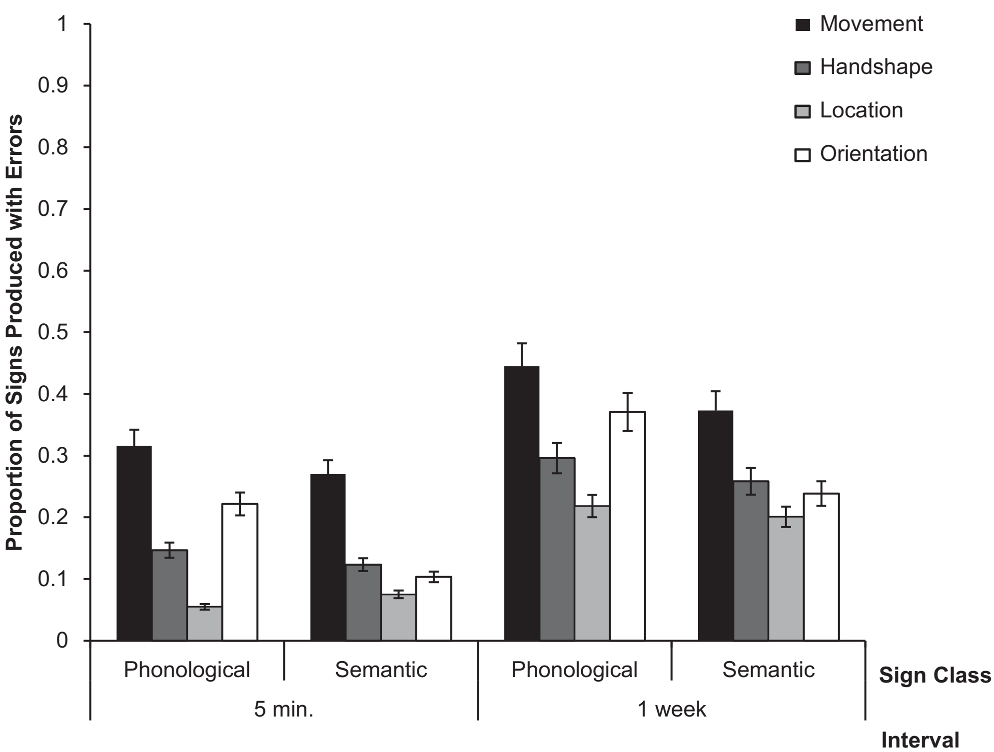

Figure 8. Sign production errors committed in Experiment 2 by participant per learning–test interval, sign class and error type. Error bars represent standard error.

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GENERAL DISCUSSION

The results of the current study demonstrate the impact of embodied action and mental imagery, as well as phonological (visual) and semantic similarity, on L2 ASL sign acquisition by adult English speakers. Specifically, the results of Experiment 1 demonstrate that enactment enhances sign acquisition, and that iconic signs are produced with fewer errors after an extended recall period. Moreover, the results of Experiment 2 demonstrate that, for signs learned via enactment, semantically related signs were recalled more accurately than phonologically related signs, and phonologically related signs were more often confused with one another on the basis of movement and orientation than semantically related signs. Considered as a whole, these results indicate that sign enactment allows novice L2 signed language learners to formulate mental representations of signs that are tightly linked to the concepts that they represent—particularly for iconic signs—resulting in superior sign recall. Thus, the results demonstrate that embodied action and mental imagery work together to facilitate signed language acquisition by improving sign encoding and recall, which are necessary for successful sign learning.

Experiment 1 examined the effects of embodied action and mental imagery on L2 sign acquisition by teaching signs to individuals unfamiliar with ASL via methods that actively engaged these processes—namely, enactment, arbitrary hand motion, referent visualisation and comprehension. The results showed that, although participants could learn the meanings of signs via any of these methods, signs learned via enactment were more likely to be recalled than signs learned via visualisation or arbitrary hand motion. These findings demonstrate that mental imagery and embodied action are most effective at promoting sign acquisition when used in conjunction with one another, rather than separately. This finding is consistent with the results of work demonstrating that gesture facilitates lexical access (Frick-Horbury & Guttentag, 1998; Lucero, Zharchuk, & Casasanto, 2014) and that gesturing when learning words in a novel L2 enhances their acquisition (Morett, 2014; Tellier, 2008). For individuals unfamiliar with signed language, enactment may increase the salience of the phonological forms of signs, which, in turn, may facilitate their association with referents through iconicity or other mnemonic devices. Consistent with this explanation, there is evidence that enactment activates the motor cortex in addition to the sensory areas of the brain, thereby enriching representations with a motor component (Porro et al., 1996). Although the neural substrates of enactment during L2 lexical learning have not yet been investigated, research has shown that viewing iconic gestures during L2 word learning activates the premotor cortex. Moreover, the same work showed that viewing meaningless hand motions during L2 word learning activates brain regions responsible for cognitive control (Macedonia et al., 2010). Considered in conjunction with the results of the current study, these findings indicate that, while meaningful embodied action (enactment) enhances L2 lexical acquisition, meaningless embodied action (arbitrary hand motion) hinders it.

Like meaningless embodied action, mental imagery did not independently facilitate L2 sign acquisition. Fewer signs were recalled when they were learned via referent visualisation, in which participants were instructed to formulate mental images of the meanings of signs, than when they were learned via enactment. Given that sign languages are processed in the visuospatial modality, the mental imagery generated through this method may interfere with sign language interpretation by overloading this modality, rather than supporting learning by supplementing the verbal channel, as it does for spoken languages (Paivio, 1990). This interpretation is consistent with research demonstrating that simultaneous engagement in multiple tasks requiring visuospatial processing detracts from performance on these tasks due to overloading of the visuospatial sketchpad of working memory, whereas simultaneous engagement in a task requiring visuospatial processing and a task requiring verbal processing does not impair performance (Kruley, Sciama, & Glenberg, 1994; Sims & Hegarty, 1997). Considered in conjunction with the positive effects of meaningful embodied action on sign learning and the less drastic decrease in sign learning resulting from arbitrary motion, this result indicates that the motor system may be better able to facilitate sign learning in its initial stages than mental imagery. This may be the case because active engagement of the motor system through enactment enriches mental representations of signs by contributing haptic information, whereas formulating mental images of referents unrelated to sign forms may not contribute much information beyond that conveyed through the visuospatial modality.

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Additionally, the haptic information contributed by sign re-enactment reflects sign forms, rather than sign meanings unrelated to sign forms. Because the current study does not directly address these possibilities, further research is needed to assess their validity. Nevertheless, the results demonstrate that enactment is a particularly effective method for hearing adults unfamiliar with signed language to learn signs because it combines meaningful embodied action with mental imagery, creating robust multimodal representations of signs in the minds of learners.

Aside from the effects of mental imagery or embodied action, the results of Experiment 1 showed that iconicity affects sign recall. Specifically, they demonstrated that more metaphorical and arbitrary signs were forgotten than iconic signs, and that iconic signs were recalled more accurately than metaphorical and arbitrary signs. These results are consistent with evidence that iconic signs are learned more easily than non-iconic signs (Lloyd et al., 1985; Thompson et al., 2012), including by hearing adults (Campbell et al., 1992; Lieberth & Gamble, 1991). Thus, they provide evidence that visual iconicity establishes a direct link between the forms of signs and their meanings. Unlike the mental images of referents elicited in the visualisation condition, which may have interfered with sign processing, visual iconicity of signs contributes to multimodal, unitary lexical representations of signs, facilitating their recollection. Nevertheless, these results are inconsistent with work indicating that hearing adults unfamiliar with ASL can identify the referents of metaphorical signs just as well as the referents of iconic signs (O'Brien, 1999). This discrepancy may be due to the differing demands of the tasks used in this study and the current study, given that the former consisted of forced-choice guessing of the meanings of unknown signs, and the latter consisted of recall of signs in response to English words conveying their meanings. While the greater difficulty of the current study may explain poorer recall accuracy for metaphorical signs relative to iconic signs, it is unclear why metaphorical signs were recalled as poorly as arbitrary signs. Future research should confirm the reliability of this effect in the context of sign recall accuracy, and should determine whether it extends to other measures of sign recollection, such as backward translation (recalling the English meaning of ASL signs) for greater quantities of learned signs.

Experiment 2 investigated how signs learned via enactment in the early stages of L2 sign acquisition are represented and organised by examining novice learners' acquisition of semantically and phonologically related signs. The results showed that more semantically related signs were recalled than phonologically related signs. Furthermore, they demonstrated that semantically related signs were produced more accurately at recall than phonologically related signs, and that more handshape and orientation errors were committed during the production of phonologically related signs than semantically related signs. These findings indicate that, for signs learned via enactment, visual characteristics of sign forms are more salient within novice L2 learners' representations—and thus, more easily confused—than semantic characteristics of referents. Furthermore, they suggest that the organisation of novice L2 learners' sign representations is based primarily on visual (phonological) characteristics, supporting the findings of previous work examining phonological and semantic organisation of sign representations in non-native signers (Mayberry & Fischer, 1989; Mayberry & Witcher, 2005). Although the current study was not designed to directly compare representations of signs learned via enactment with representations of signs learned via other methods, the similarity of the results of the current study and the results of these previous studies of sign representation indicate that novice hearing adult L2 sign learners' representations are predicated primarily on the visual similarity, rather than the semantic similarity, of signs.

On the other hand, the observation that semantically related signs were not routinely confused with one another suggests that enactment may help novice hearing adult L2 sign learners to learn the semantic distinctions between signs more effectively. In contrast to phonologically related signs, participants recalled more signs correctly and committed fewer movement and orientation errors when producing semantically related signs. These findings suggest that, although the visual features of sign forms may be more salient than the semantic features of sign referents in the representations of novice L2 sign learners, learners can associate signs with their referents effectively, and can classify signs according to their semantic characteristics, as well. Because the current study did not examine the sign representations created under conditions other than enactment, it could not provide direct evidence that enactment increases the salience of the semantic relationships between signs. However, the magnitude of errors committed for phonologically related signs in the current study was lower than that observed in Mayberry and Fischer (1989) for non-native ASL signers' performance on a sentence shadowing task. This suggests that, for novice hearing L2 sign learners, enactment strengthened the links between signs and their referents, increasing the salience of sign referents and highlighting the semantic relationships between them. Further research is necessary to directly compare how signs learned via enactment and sign viewing are organised via semantic and visual (phonological) characteristics in the minds of novice adult learners. Nevertheless, the superior recall accuracy for semantically related signs relative to phonologically related signs resulting from enactment supports embodied theories of language processing by indicating that meaningful embodied action (i.e., enactment) strengthens the conceptual links between sign referents, resulting in improved encoding and recall of signs by novice adult hearing L2 sign learners.

Overall, the results of the current study demonstrate that embodied action, mental imagery and iconicity play key roles in L2 signed language acquisition by strengthening the associations between the forms and meanings of signs. This strengthening likely highlights the semantic relationships between representations of signs, reducing the amount of movement and orientation errors during sign learning. While the results provide evidence that mental imagery concerning sign referents and arbitrary motion may hinder initial L2 sign learning, they also demonstrate that enactment, which encompasses both mental imagery and embodied action, facilitates sign learning. Thus, the results indicate that this type of mental imagery and embodied action can only enhance sign learning when used in combination. Moreover, the finding that iconic signs are recalled more accurately than metaphorical and arbitrary signs indicates that mental imagery cued by the forms of signs enhances sign-referent association. Taken together, these findings suggest that enactment and iconicity help novice L2 sign learners to create robust and detailed lexical sign representations, facilitating sign encoding and recall. As such, the results indicate that these factors enhance sign learning in hearing adults, serving as effective tools to jumpstart signed language acquisition in this population.

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