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Temporal Overlap Between Gestures and Speech in Poststroke Aphasia: Is There a Compensatory Effect?

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ABSTRACT

Purpose: If language production is impaired, will gestures compensate? Evidence in favor of this prediction has often been argued to come from aphasia, but it remains contested. Here, we tested whether thought content not present in speech due to language impairment is manifested in gestures, in 20 people with dysfluent (Broca's) aphasia, 20 people with fluent (Wernicke's) aphasia, and 20 matched neurotypical controls.

Method: A new annotation scheme was created distinguishing types of gestures and whether they co-occurred with fluent or dysfluent/absent speech and were temporally aligned in content with coproduced speech.

Results: Across both aphasia types, noncontent (beat) gestures, which by their nature cannot compensate for lost speech content, constituted the greatest proportion of all types of gestures produced. Content (i.e., descriptive, referential, and metaphorical) gestures were largely coproduced with fluent rather than dysfluent speech and tended to be aligned with the content conveyed in speech. They also did not differ in quantity depending on whether the dysfluencies were eventually resolved or not. Neither aphasia severity nor comprehension ability had an impact on the total amount of content gesture produced in people with aphasia, which was instead positively correlated with speech fluency.

Conclusions: Together, these results suggest that gestures are unlikely to have a role in compensating for linguistic deficits and to serve as a representational system conveying thought content independent of language. Surprisingly, aphasia rather is a model of how gesture and language are inherently integrated and aligned: Even when language is impaired, it remains the essential provider of content.

When communicating, people naturally use gestures for expressing ideas, intentions, or personal and emotional feelings (Knapp & Hall, 1997). McNeill (1992) defines *gesture* as arm and hand movements that synchronize with speech, indicating integration with verbal communication, subdividing gesticulations into iconic, metaphorical, deictic, and beat gestures. While iconic gestures represent aspects of the referents of the accompanying speech by their shape or manner of execution and, thus, capture descriptive aspects of such content, deictic gestures are pointing movements used to refer to a concrete direction, object, or point in space associated with a discourse referent. We capture these descriptive and referential gestures as *content* gestures in what follows, whereas *beat* gestures are small, repetitive, and rhythmic movements that do not represent specific content elements from the speech.

While cospeech gestures associate with language by definition, this association is consistent with a number of possible views on the relation between the gesture and language systems. While it is natural to conceptualize gestures as a form of "nonverbal" communication, the view of such gestures as being nonverbal has long been challenged (McNeill, 1985). Instead, speech and gesture form an inherently integrated mode of expression (Graziano & Gullberg, 2018; Kendon, 1980; McNeill, 1992). At the

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same time, conceptual frameworks prevail in which gestures are separated from language. Thus, in developmental studies, gestures are often depicted as reflecting a communicative capacity preceding and providing a nonverbal foundation for language acquisition, predicting its later course and facilitating its processing (e.g., lexical retrieval; Liszkowski, 2008; Özçalışkan & Goldin-Meadow, 2005; Pine et al., 2007). Similarly, gesture production in adult populations defined by language processing difficulties, such as people with poststroke aphasia (PWA), has often been interpreted as manifesting a compensatory role of gesture in relation to language, based on evidence such as higher gesture rates (Rose, 2006). Such compensation is naturally understood as implying that gesture and speech are alternative forms of communicating the same thought contents or messages, such that, if speech fails, gesture steps in (Herrmann et al., 1988; Sekine et al., 2013).

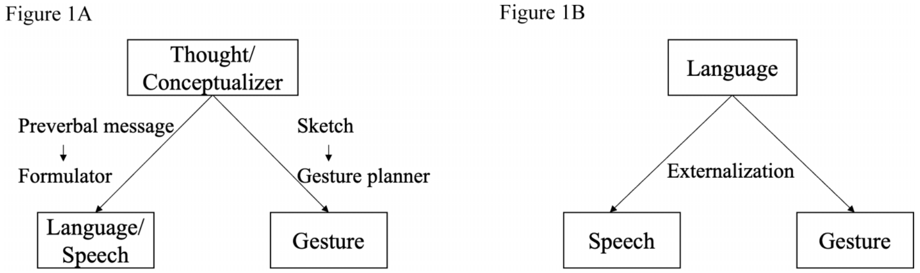
Some theoretical models of gesture production directly support this prediction. In particular, the sketch model (de Ruiter, 2000), which is influenced by both McNeill's growth point theory (1992) and Levelt's (1989) classical speech production model, suggests that speech and gesture content derives from a nonverbal "message-level content" generated by the "conceptualizer" (de Ruiter, 2000; de Ruiter & de Beer, 2013). If speech and gesture are viewed as two possible communicative channels for the same nonverbal thought content, then it should be possible for this thought content to be preserved when speech is impaired. The model thus naturally predicts that the conceptualizer would seek gesture as an alternative way to communicate: "Speech failure could then be compensated for by the transmission of a larger part of the communicative intention to the gesture modality" (de Ruiter, 2000, p. 293).

A considerable number of experimental studies have supported this prediction driven by theoretical models. For example, van Nispen et al. (2017) suggested that a great proportion of gestures produced by PWA conveyed information that was absent in their speech, specifically pointing emblems and iconic gestures (where emblems are defined to be gestures that convey conventionalized and culture-specific meaning). Kong et al. (2015) found that gesture frequency in PWA was significantly positively correlated with the overall aphasia severity and negatively correlated with their verbal semantic skills. Similarly, in a follow-up study, Kong et al. (2017) showed that the increased gesture-to-word ratio in PWA was predicted by their reduced ability to produce complete sentences and the high frequency of speech dysfluencies, all seemingly providing evidence in support of the hypothesis that the verbal impairment was compensated for by the production of gestures.

This compensation hypothesis, on the other hand, does not sit well with McNeill's (1985) challenge to the idea that gestures are "nonverbal," that is, are in fact an aspect of language. If they are in fact verbal, we expect that they should not be able to compensate for verbal content that is missing. McNeill's (1992) explicit model of speech and gesture nonetheless leaves room for interpretation in this regard. In particular, if speech and gesture feed on the same communicative intentions for their contents (called "holistic representations" or "growth points" in this model), as with de Ruiter's sketch model above, then it is not obvious why there should not be compensation: If the communicative intentions are nonlinguistic in nature, we might naturally expect that they should still be available when speech breaks down, and hence, that gesture should be able to express them when speech cannot. On the other hand, the nature of this conceptualizer or the "preverbal message" level has remained notoriously unclear. As Papafragou and Grigoroglou (2019) noted, "relatively few studies have addressed the contents of preverbal representations" (p. 1117). At the same time, they listed a number of necessary and sufficient features that such messages are to have, in order for the next stage of processing corresponding to linguistic formulation to come out right. This includes numerous linguistic features, such as a propositional form, reference and predication, thematic and aspectual structure, and tense. In short, it appears that, at least to some extent, messages generated by the conceptualizer are structured linguistically before language at this cognitive level is mapped onto *speech*. If so, the prediction changes: If content generated at this level is in fact linguistic in nature, then, if language fails, gesture should have no content to convey. This would hold insofar and as long as gesture feed on the same propositional representations generated at this level, even if, in the gestural channel, these same representations are first transduced into an imagistic and spatiotemporal format (de Ruiter, 2000).

Whether or not to predict compensation on theoretical grounds thus depends on a number of foundational issues and ultimately on how language relates to the thought it expresses. If the two are fundamentally distinct (Fedorenko & Varley, 2016; Fodor, 2001), language is not the unique or primary source of content, which would be consistent with a possible compensatory effect through gesture accessing the same thought content. If they are not, and language mediates thought processes (Baldo et al., 2005, 2010, 2015; Hinzen & Sheehan, 2015), or if the content of thought ultimately derives from that of language (Davidson, 2004; Dummett, 1993), compensation is less expected. On this latter view, a natural prediction would rather be that gesture will not provide contents that language does not: Language and gesture cannot ultimately go separate ways, that is, the content of gesture and language should *align*. Figure 1 represents this basic dichotomy schematically.

Figure 1. Two basic models of speech and gesture and their dependence on thought. In model Figure 1A, which is based on the work of de Ruiter (2000, p. 298), speech and gesture both feed on nonlinguistic content. In Figure 1B, speech and gesture express or feed on the same linguistic content, inconsistent with compensation when language is impaired.



Apart from theoretical considerations, some methodological and empirical problems have challenged the compensation hypothesis as well. Starting with methodological problems, in both of the abovementioned studies by Kong et al., gesture types were not distinguished when calculating the gesture-to-word ratios, hence including the vast majority of non–content-carrying unidentifiable and beat gestures, which cannot play a role in compensating speech content. A number of other studies have used highly controlled experimental designs with cartoon fragments depicting various motion events with vivid visual image, creating opportunities for PWA to immediately imitate the objects/events present in the clips. Thus, Akhavan et al. (2018) have used short movie clips depicting different motion events to elicit gesture production in PWA and concluded that PWA heavily relied on iconic gestures to compensate for their language impairment, and the degree of such compensation was correlated with the extent of language impairment. Similarly, a recent study by de Beer et al. (2020) found that the narration task of retelling short fragments from cartoon clips evoked a higher gesture-to-word ratio than the spontaneous conversation, and it also encouraged PWA to use more iconic gestures to compensate for their verbal limitations (see also the work of Dipper et al., 2015). However, iconic gestures and pantomimes were subsumed in the coding scheme. This is problematic in that unlike iconic gestures, pantomime by definition represents content through actions without speech, which is further supported by evidence that the production of pantomime relies on different resources than cospeech gestures (Bartolo et al., 2003). Avoiding the confound of visual priming, a study by Sekine et al. (2013) used a detailed gesture coding system to analyze gestures spontaneously produced by individuals with a number of aphasia types in personal narrative interviews from AphasiaBank. In line with the compensation hypothesis, they found that PWA in general gestured more frequently than healthy controls and that the frequency of meaning-laden gestures (i.e., iconic gestures, emblems, and pantomimes) was greater in the Broca's than in the Wernicke's, anomic, and control groups. However, the temporal overlap between gestures and speech was not investigated, which does not allow addressing the question of whether these overproduced gestures by PWA were accompanied by speech or not. This is crucial to understand whether gestures had taken over from speech and were functioning by themselves.

As for empirical problems with evidence for compensation, So et al. (2009) found that gestures of neurotypical speakers paralleled rather than compensated for underspecifications in speech when describing scenes to an experimenter. Graziano and Gullberg (2018) challenged the gesture and language acquisition theories assuming a compensatory role for gestures by showing that gesture stops at the same time as speech stops in healthy speakers. Cicone et al. (1979) suggested that the gestures of PWA resembled their speech output, contrary to the idea that PWA spontaneously enhance their communicative efficacy through the use of gesture. Similarly, Glosser et al. (1986) found a significant negative correlation between gesture complexity and measures of linguistic complexity for PWA. Using a rating experiment, Mol et al. (2013) showed that gestures produced by people with severe aphasia were less informative than those produced by people with moderate aphasia (but see the work of Hogrefe et al., 2013).

In summary, despite considerable evidence in favor of the compensation hypothesis and its consistency with some theoretical models, it remains open and of considerable foundational interest. In addition to the problems affecting it as reviewed above, the majority of studies have also been conducted in either small samples or in heterogeneous groups of individuals with different types of aphasia. Even in studies that have made a distinction between nonfluent and fluent aphasia, the latter group often includes a majority of people with anomic aphasia (Kong et al., 2015, 2017), leaving aside Wernicke's aphasia, whose gesture profile has not been specifically investigated in large samples so far (see, e.g., Ahlsén, 1991; Sekine & Rose, 2013).

Our goal here was to clarify evidence for and against the compensation hypothesis, through a new annotation scheme for gestures occurring in spontaneous connected speech, which focused on content gestures (specifically referential, descriptive, and metaphorical ones), while also distinguishing these from emblem, pantomime, and beat gestures. This scheme was applied to the speech of two major types of aphasia, namely, Broca's aphasia (BA) and Wernicke's aphasia (WA), which were compared to matched neurotypical controls (healthy controls [HCs]). The motivation for selecting these two aphasia types was previous evidence that aphasia types and speech fluency have an influence on gesture production (Sekine & Rose, 2013), and BA and WA are partially defined as nonfluent and fluent aphasia, respectively. Moreover, unlike many studies that mainly used anomic aphasia as representative of the fluent type, we focused on WA since it is defined by problems in the auditory speech perception and comprehension of word meaning, as well as in semantic processing (Robson et al., 2012). Such problems may have a distinctive effect on gesture production and the specific question arises whether gestures can compensate for problems of this type, leading to potential differences between the BA and WA groups. Early research by Cocks et al. (2013) has shown that impaired semantic knowledge in aphasia is associated with a higher frequency of word finding difficulties that contained gestures. Nonverbal semantic processing abilities has also been found to have an impact on the production of hand gestures (Hogrefe et al., 2012) and on gesture-enhanced lexical learning (Kroenke et al., 2013).

For all content gestures, we asked whether their temporally overlapping speech was fluent, dysfluent, or absent, in order to test predictions consistent with a compensation effect, firstly that gestures in PWA predominate precisely when speech is dysfluent or absent. This would not be to deny that even gestures coproduced with fluent speech could add aspects of content (e.g., through their iconic format) and ensure or enhance understandability even when redundant with speech content (de Ruiter et al., 2012). Rather, this first prediction would be tuned to our conceptualization of compensation as one modality taking over the function of another modality. Current evidence on this prediction is inconsistent. Lanyon and Rose (2009) found that PWA produced a significantly greater amount of gestures during instances of word finding difficulties than during fluent speech, and meaning-laden gestures (iconic, pantomime, and emblem gestures) accounted for the majority of all gesture production during word retrieval difficulties. However, Kong et al. (2018) suggested that gestures were not necessarily employed when PWA encountered lexical retrieval problems and when they did experience such difficulties that nonidentifiable gestures were most frequently used.

A second prediction from compensation that we explored was that the contents of gestures and of accompanying speech would not need to align and that gestures co-occurring with dysfluent speech would be linked to when these dysfluencies are resolved (see, e.g., the work of Kistner et al., 2019; Krauss et al., 2000). However, evidence in this regard is again inconsistent. The aforementioned study of Lanyon and Rose (2009) found that the amount of gesture produced by PWA during resolved versus unresolved word retrieval difficulties did not differ significantly. Similarly, Kong et al. (2018) observed that the employment of coverbal gestures was not associated with the success of lexical retrieval. Finally, we explored the prediction that the more severe aphasia or comprehension impairment is, or the more dysfluent the speech is, the more content gestures would be produced. Our three specific research questions were as follows.

1. Are content gestures significantly more produced by PWA than controls, and do the gesture profiles diverge depending on whether the aphasia is of the fluent or dysfluent type?
2. Do content gestures in PWA tend to be coproduced with speech or not? If so, does the speech tend to be fluent or dysfluent, are speech and gestures aligned in content, and do gestures impact on whether dysfluencies are resolved or not?
3. Are there any correlations between the frequency of content gesture production and measures of aphasia severity, comprehension ability, and speech fluency?

Method

Participants

A total of 60 individuals were included in this study, including 20 people with Broca's aphasia (PWBA; M_{age}: 65.1 years old; range: 43.3–85.4 years old), 20 people with Wernicke's aphasia (PWWA; M_{age}: 66.7 years old; range: 42.6–91.7 years old), and 20 HCs (M_{age}: 67.4 years old; range: 44.3–87.8 years old). Data were obtained from AphasiaBank (https://aphasia.talkbank.org/; MacWhinney et al., 2011), which is a shared database of multimedia interactions for the study of aphasia for researchers worldwide. As there are relatively fewer samples of WA in the database, demographic data from PWWA in the database were first extracted as a reference group, based on which we selected PWBA by matching their aphasia severity as measured by the aphasia quotient in the Western Aphasia Battery, age, and years of education with PWBA. Finally, a group of HC participants were selected by matching their age and educational level with the clinical group. All of the participants with aphasia satisfied the inclusion criteria of (a) English as their primary language, (b) an aphasia quotient ranging from 28 to 75 (from the most severe end to moderate aphasia), (c) at least 6 months poststroke onset (the aphasia duration for PWBA: M = 5. 93 years, SD = 3.66 years, and for PWWA: M = 5. 19 years, SD = 4.30 years), (d) a single stroke resulting in left-hemisphere lesions, and (e) premorbidly right-handed. The control group consisted of participants with English as their primary language and no history of stroke, head injury, or other neurological and psychiatric conditions.

Speech Samples

The speech data in the AphasiaBank database consisted of participants' performance on discourse tasks across four genres, including personal narratives, picture descriptions, Cinderella storytelling, and procedure discourse. Considering that the last three tasks involved either predetermined content or visual stimuli and that our aim was to access gestures spontaneously produced during natural conversation, we thus restricted our analysis in this study to task from the first genre, which encompassed structured interviews where the investigators required participants to retell their stroke experience (or an injury story in the case of HCs), coping with the condition, and an important event that molded their life. The complete samples of spontaneous conversation from the structured interview section were analyzed for each participant. On average, the sample length for the BA group was 6 min, for the WA group was 6 min 49 s, and for the HC group was 4 min 2 s.

Annotation

To investigate the gestures that participants spontaneously produced, we extracted the media file of the structured interview section from the database for each participant and linked it to its corresponding speech transcript and analyzed each one. Annotation was carried out using ELAN (https://archive.mpi.nl/tla/elan). The basic unit of analysis was a gesture defined as the period from the onset of a hand(s) movement to its end point.

Coding of Gesture

Annotation proceeded by first identifying gestures and then classifying them as either content gestures or not. *Content* gestures were subdivided as descriptive, referential, or metaphorical. The remaining gestures that did not fall into this category mainly include emblems, pantomimes, and beat gestures. Unlike in previous studies, which defined emblems as meaning-laden or content-carrying gestures, we excluded emblems in our category of content gestures as they convey a form of conventionalized meaning and are typically produced without speech. Pantomimes were also excluded from this category, as they are produced without accompanying speech by definition (McNeil, 2005, p. 5), and are more concerned with performing sequences of actions than symbolically referring to them. The definitions and examples of each gesture type are as listed below, which are largely in line with previous gesture classification schemes (Kendon, 1980; McNeill, 1992).

1. Descriptive gestures are gestures that provide characteristic features of some identified objects, for example, its shape and size or the manners of an action.
2. Referential gestures indicate either concrete referents in the physical environment (e.g., a body part) or implied and imaginary persons, objects, times, spaces, or directions related to the conversational context. The hand shape of this gesture canonically takes the form of a pointing gesture.
3. Metaphorical gestures are visual representations of abstract concepts or ideas, such as *love, thinking, and better*. For example, a participant was saying, "I love the kids," while holding the hand from the heart toward outside to mean *loving*, or saying, "to feel better," while lifting the hand from down to up in front of the chest to mean *better*.
4. Emblems are gestures that convey conventionalized and culture-specific meaning, such as the "thumbs up" gesture meaning "good" or "well done." They can usually be understood without the accompanying speech.
5. Pantomimes are defined as "hand-as-hand" movements that demonstrate objects or actions in complex and sequential movements, mostly produced in the absence of speech.
6. Beat gestures are brief, repetitive, and rhythmic hand movements that do not express semantic meaning.

During the annotation process for PWA in this project, we additionally identified two categories of gesture that did not fit into any of the above six classifications. One was "Unidentifiable," a category that was used when a gesture appeared to be produced but its meaning or function could not be identified. For example, moving the hands up and down or from side to side on the table or in front of the chest is often accompanied by the absence of speech, dysfluencies, or unidentifiable speech content. These are different from beat gestures as defined below in that beat gestures are often rhythmic and produced simultaneously with the flow of speech content, functioning so as to accentuate speech prosody. Another category contains gestures expressing content, which is unclear and obscure, coded as "Content-unclear."

Two further decisions were made regarding gesture classification. First, many PWA tend to write in the air or against a flat surface when they cannot produce what they intend to say. These were not counted as gestures for the purposes of the present annotation scheme, which focused primarily on *content* gestures. Second, holding up fingers to indicate numbers up to five was not annotated, since they are neither referential nor descriptive of some object's features. The justification for excluding numbers and letters is that, like emblems, they convey conventionalized meaning, forming a category different from those gestures conveying referential meaning.

Coding of Speech

When the type of a gesture was identified as "Content" (descriptive, referential, metaphorical, content-unclear), we subsequently analyzed it with respect to whether it temporally overlapped with the production of speech or not. If the content gesture was produced with no accompanying speech, "No speech" would be annotated. If, on the other hand, there was a temporal overlap, we then determined whether the accompanying speech was fluent or dysfluent. If it was fluent, we determined whether the speech and gesture were aligned in content or not. "Fluent-aligned" would be annotated if both speech and gesture expressed similar meaning. Otherwise, "Fluent-nonaligned" would be coded (i.e., gesture conveyed content different from that of speech). In cases where the accompanying speech was dysfluent, "Dysfluency" would be coded.

Coding of Referential Anomalies of Gesture and Speech

If a referential gesture was coproduced with *fluent speech*, which was further *aligned* in content with the accompanying speech, we checked whether the referent could be understood from the context or not. For example, when a referential gesture was coproduced with a pronoun without an antecedent and whose referent could not be determined, "Referential anomaly" would be coded. This was the case when we detected an error occurring in the fluent-speech plus referential-gesture combination, given the speech context (e.g., a pronoun or a locative was produced without antecedent, making it unclear what was referenced) or by the physical environment where the referential gesture was not referring to an identifiable object. For example, a participant produces the utterance "they were doing it," where a referential gesture to the head was coproduced with "it" and it is not clear either from the speech or from the gesture what is being referred to, or the utterance "That one I do it here" where a referential gesture was coproduced with "that," and the reference is again not clear. Importantly, referentially anomalous gestures were often coproduced with words such as *there, here*, and *now*, or pronouns such as *me, she/her, he/him, they/them*, which occurred frequently in the speech of PWA, particularly PWWA. However, these words are formally phrases, and reference is not a word-level phenomenon (de Ruiter, 2000; Hinzen & Sheehan, 2015).

Resolution of Dysfluencies

Dysfluency was defined according to our adaptation of the list of indicators of word finding difficulties by Kistner et al. (2019). In this study, instances of dysfluency include repetitions; fillers such as *uh* and *um*; phonological paraphasias, such as saying *dat* instead of *cat*; semantic paraphasias, such as saying *girl* instead of *boy*; and neologisms (i.e., using a nonword in place of the intended word). If the accompanying speech was annotated as "dysfluent," we further checked whether the given dysfluency was eventually resolved or unresolved, that is, whether the target word was successfully retrieved or not.

Table 1 lists the composite variables generated from the above scheme and analyzed for each participant. Figure 2 summarizes the flow of the annotation process.

Reliability of Coding

Following the annotation manual described above, the first author coded the entire samples and reviewed them for a second time to check the initial annotations. During the annotation process, the coder noted all cases that were difficult to decide in each sample and met weekly with the senior author to discuss and resolve them. Decisions made during discussion guided later coding. In order to establish the interrater reliability of coding, a third, independent rater ignorant of the aims of the study was trained on the annotation manual and coded 15% of the data randomly selected from each group. Independent rating samples were checked against the original ratings on a point-to-point basis, and disagreements were attempted to be resolved by discussion to reach consensus from the two raters. Final reliability was calculated for all variables (a composite variable combining gesture type and speech fluency in the case of *content gestures*, or a single gesture type in the case of other gestures types) by dividing the total number of points the two ratings agreed by the sum of the total points possible. Mean agreement between raters was 85.3% for BA, 81.4% for WA, and 93.1% for HC.

Analysis

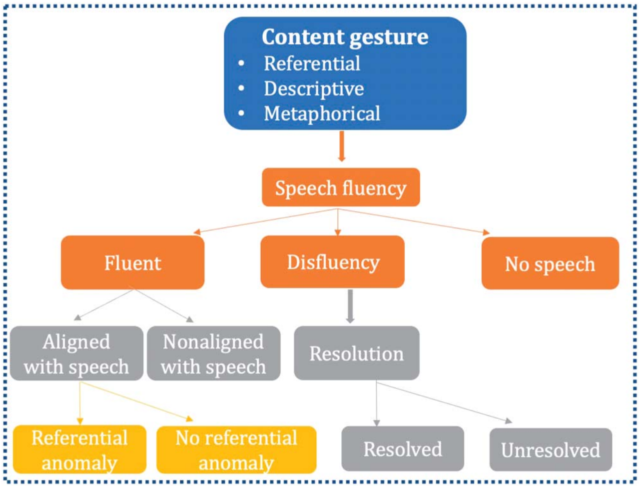
The analysis proceeded in four stages. First, we determined the prevalence of different types of gestures based on their respective proportions out of the total number of utterances each participant produced (see Figure 3). This information provided by descriptive statistics was designed to mainly get an overview of gesture proportions in the categories of interest. Second, to answer our first research questions concerning differences in gesture

Table 1. A summary of the composite variables investigated.

Composite variables	Abbreviations
1. *Content gestures* that were coproduced with *fluent speech*.	*Content-fluent*
2. *Descriptive gestures* that were coproduced with *fluent speech*.	*Descriptive-fluent*
3. *Referential gestures* that were coproduced with *fluent speech*.	*Referential-fluent*
4. *Content gestures* that were coproduced with *fluent speech* and *aligned* in content with the accompanying speech.	*Content-fluent-aligned*
5. *Descriptive gestures* that were coproduced with *fluent speech* and *aligned* in content with the accompanying speech.	*Descriptive-fluent-aligned*
6. *Referential gestures* that were coproduced with *fluent speech* and *aligned* in content with the accompanying speech.	*Referential-fluent-aligned*
7. *Referential gestures* that were coproduced with *fluent speech* and contained an anomaly shared by both gesture and speech.	*Content-referential anomaly*
8. *Content gestures* that were coproduced with *fluent speech* and *nonaligned* in content with the accompanying speech.	*Content-fluent-nonaligned*
9. *Content gestures* that were produced with *dysfluencies* or *in the absence of speech.*	*Content-dysfluency-no speech*
10. *Descriptive gestures* that were produced with *dysfluencies* or *in the absence of speech.*	*Descriptive-dysfluency-no speech*
11. *Referential gestures* that were produced with *dysfluencies* or *in the absence of speech.*	*Referential-dysfluency-no speech*
12. *Content gestures* that were coproduced with *dysfluencies* that were *resolved.*	*Content-dysfluency-resolved*
13. *Content gestures* that were coproduced with *dysfluencies* that were unresolved.	*Content-dysfluency-unresolved*

production across groups, a set of negative binomial regression models were applied using the MASS package (Version 7.3–54; Venables & Ripley, 2002) in R (https://www.R-project.org/) to compare across the three groups in the six types of gestures (referential, descriptive, metaphorical, emblem, pantomime, and beat) and the two composite variables (referential-fluent-aligned and descriptive-fluent-aligned). Negative binomial regression is a generalization of Poisson regression but more flexible. It has a clear advantage over Poisson regression in that it does not make the mean equal to variance assumption and performs well in addressing overdispersion resulting from outliers or other factors (Payne et al., 2018). In each of the model, we defined *Group* as a categorical predictor and an offset term containing the *total number of utterances*, which was used to account for the possibility that gestures were more or less produced as an effect of variation in the number of utterances produced by different participants. This offset term also served to convert the outcome of the predicted variable from a count into a rate (i.e., the incidence of gesture per utterance).

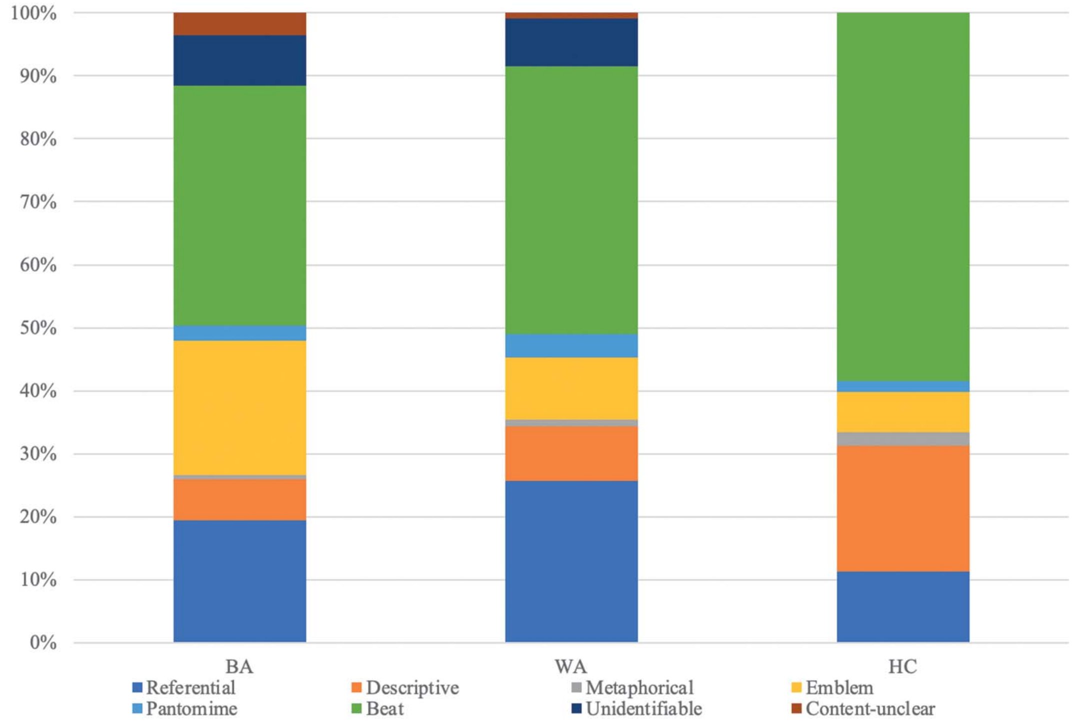
Figure 2. A schematic representation of the annotation scheme.



An omnibus test was applied to each model to first access the overall significance of the predictor Group. A significant omnibus test was followed by post hoc pairwise comparisons with the emmeans package (Version 1.6.0), to evaluate the relative effect of groups on the production of different types of gestures. p values are presented in their adjusted form with the Tukey method for comparing a family of three estimates. For any significant omnibus test, follow-up pairwise comparisons provide an estimated incidence rate ratio for each group contrast (e.g., HC/BA, HC/WA, BA/WA), and its statistical significance. These ratios were obtained by dividing the estimated incident rate of a certain variable for one group by that for another group, in which a ratio greater than 1.0 indicates that the likelihood for this variable to occur in the former group is higher than that in the latter group, and a ratio less than 1.0 indicates the opposite.

Because the four categories of gesture, *Unidentifiable, Content-unclear, Content-fluent-nonaligned*, and *Content-referential anomaly*, were not produced once by the control participants, the same model to assess potential differences for these four variables was used only in the clinical group. The model output provides an estimated incidence rate for the reference group (also "Intercept," which we set as the BA group) and the incidence rate ratio relative to the Intercept for the WA group, as well as its statistical significance.

Figure 3. Distribution of each type of gesture relative to the total number of utterances in Broca's aphasia (BA), Wernicke's aphasia (WA), and healthy control (HC), respectively.



Next, to address our second research question concerning temporal alignment patterns between gestures and accompanying speech in the clinical group, we fitted five mixed-effects negative binomial regression models using the glmmTMB package (Version 1.0.2.1; Brooks et al., 2017) in R to evaluate any potential difference in the estimated incidence rates of five gesture contrasts we were interested in, in the clinical group, for example, *Content-fluent* versus *Content-dysfluency-no speech* (further distinguishing *descriptive and referential*), *Content-fluent-aligned* versus *Content-fluent-nonaligned, Content-dysfluency-resolved* versus *Content-dysfluency-unresolved*. Each model included a fixed effect of the gesture contrast (two levels: e.g., *Content-fluent* vs. *Content-dysfluency-no speech*), a random intercept for subject, and an offset variable of total number of utterances.

Finally, to answer our last research question concerning relations between content gesture production and clinical aphasia measures, Spearman correlation analyses were performed to access the potential association between the production of content gestures (a relative ratio calculated by dividing the total number of content gestures by the total number of utterances) and measures of aphasia severity, comprehension, and spontaneous speech (including both information content and fluency) determined by the Western Aphasia Battery test. Only statistically significant results were reported in the next section.

Results

Figure 3 presents the relative proportion of all eight types of gestures (referential, descriptive, metaphorical, emblem, pantomime, beat, unidentifiable, and content-unclear) produced relative to the total number of utterances by individuals in each of the three groups. Across all three groups, beat gestures accounted for the greatest proportion among all gesture types (59% in HC, 42% in WA, 38% in BA). However, in the clinical groups, referential gestures took up the second largest proportion in WA (26%) and third largest proportion in BA (19%), whereas in the control group, they accounted for only 11%, and it was descriptive gestures that occupied the second largest proportion (20%). This was almost twice the proportion of descriptive gestures in PWWA (9%) and 3 times that in PWBA (7%).

Our first research question concerned differences in gesture production across groups. Table 2 shows the omnibus test results of the overall model effect for the six types of gestures (referential, descriptive, metaphorical, emblem, pantomime, and beat). *Group* was found to be a significant predictor for the use of referential gestures, with post hoc pairwise comparisons showing that PWWA and PWBA both produced significantly more *referential gestures* than controls (HC/BA: ratio = 0.263, $p < .001$; HC/WA: ratio = 0.169, $p < .001$; see Table 2). Importantly,

Table 2. Statistical significance for possible group differences across the three groups.

Variable	Model	*df*	Deviance	*p* value	Contrast	Ratio	*SE*	*z* ratio	*p* value
Referential	NBRM	2	41.86	< .001	HC vs. BA	0.263	0.077	−4.563	< .001
					HC vs. WA	0.169	0.047	−6.341	< .001
					BA vs. WA	0.641	0.156	−1.823	.162
Descriptive	NBRM	2	2.635	.268					
Metaphorical	NBRM	2	1.2652	.531					
Emblem	NBRM	2	35.469	< .001	HC vs. BA	0.150	0.050	−5.736	< .001
					HC vs. WA	0.270	0.089	−3.960	< .001
					BA vs. WA	1.800	0.477	2.222	.068
Pantomime	NBRM	2	8.1691	.0168	HC vs. BA	0.240	0.183	−1.877	.146
					HC vs. WA	0.132	0.095	−2.806	.014
					BA vs. WA	0.548	0.327	−1.009	.571
Beat	NBRM	2	10.101	.006	HC vs. BA	0.658	0.160	−1.721	.197
					HC vs. WA	0.471	0.111	−3.203	.004
Descriptive_fluent_aligned	NBRM	2	3.6706	.1596					
Referential_fluent_aligned	NBRM	2	35.638	< .001	HC vs. BA	0.363	0.117	−3.146	.005
					HC vs. WA	0.172	0.052	−5.801	< .001
					BA vs. WA	0.474	0.127	−2.784	.015

Note. *SE* = standard error; NBRM = negative binomial regression model; HC = healthy control; BA = Broca's aphasia; WA = Wernicke's aphasia.

referential gestures produced by PWWA were also more likely to contain anomalies than those produced by PWBA (WA/BA: ratio = 6.70, $p = .014$); see Table 3, which displays group differences between BA and WA in the four categories of gestures that were only seen in the clinical group. Turning from content gestures to other gestures types (emblem, pantomime, beat, and unidentifiable), PWWA and PWBA produced significantly more emblems than the controls (HC/BA: ratio = 0.150, $p < .001$; HC/WA: ratio = 0.270, $p < .001$); relative to controls, PWWA also produced significantly more pantomime (HC/WA: ratio = 0.132, $p = .014$) and beat gestures (HC/WA: ratio = 0.471, $p = .004$).

Our second research question concerned temporal alignment between content gestures and accompanying speech in the clinical group. Table 4 displays the statistical significance for five gesture contrasts in the clinical group as a whole. Results showed that content gestures were 6.49 times more likely to be coproduced with *fluent* speech compared with those produced in company with dysfluencies or in the absence of speech ($p < .001$) and this pattern applied to both descriptive and referential gestures. Furthermore, those content gestures that were coproduced with fluent speech were significantly *aligned* as opposed to nonaligned with the accompanying speech, with the relative incidence ratio being as high as 12.74. Finally, the production of content gestures made no difference as to whether dysfluencies were eventually *resolved* or not (resolved/unresolved: ratio = 1.4, $p = .373$).

Our third and final research question concerned relations between content gesture production and clinical aphasia measures. Correlation results (see Table 5) showed that there was no significant correlation between the production of content gestures and the measures of aphasia severity and comprehension capacity. However, content gestures that coproduced with fluent speech, as well as the subdivision of referential-fluent gestures, positively correlated with clinical measures of spontaneous speech fluency. Moreover, a significant positive association was found

Table 3. Statistical significance for possible group differences between the Broca's aphasia (BA) group and the Wernicke's aphasia (WA) group.

Variable	Model	Predictors	Incidence rate ratios	CI	Statistic	*p* values (intercept)	*p* values
Unidentifiable	NBRM	BA (Intercept)	0.04	0.02–0.07	−11.29	< .001	
		WA	1.17	0.55–2.51	0.42		.677
Content_unclear	NBRM	BA (Intercept)	0.02	0.01–0.07	−6.58	< .001	
		WA	0.27	0.04–1.87	−1.42		.156
Content_referential_anomaly	NBRM	BA (Intercept)	0.00	0.00–0.01	−8.71	< .001	
		WA	6.70	1.60–35.86	2.47		.014
Content_fluent_nonaligned	NBRM	BA (Intercept)	0.01	0.00–0.02	−11.07	< .001	
		WA	1.85	0.66–5.54	1.11		.268

Note. CI = confidence interval; NBRM = negative binomial regression model.

Table 4. Statistical significance for four gesture contrasts in the clinical group.

		Fixed effect					Random effect		
Predictors	**Model**	**Incidence rate ratios**	**CI**	**Statistic**	***p* value (intercept)**	***p* value**	σ^2	τ_{00}	**ICC**
Content_dysfluent_no speech (Intercept)	GLMM:NB	0.03	0.01–0.04	−12.68	< .001		0.35	0.20	.36
Content_fluent		6.49	4.07–10.35	7.84		< .001			
Referential_dysfluent_no speech (Intercept)	GLMM:NB	0.02	0.01–0.03	−11.96	< .001		0.44	0.21	.33
Referential_fluent		6.56	3.82–11.26	6.82		< .001			
Descriptive_dysfluent_no speech (Intercept)	GLMM:NB	0.01	0.00–0.01	−13.19	< .001		0.75	0.22	.23
Descriptive_fluent		6.08	3.19–11.59	5.48		< .001			
Content_fluent_nonaligned (Intercept)	GLMM:NB	0.01	0.01–0.02	−13.25	< .001		0.35	0.31	.48
Content_fluent_aligned		12.74	7.34–22.11	9.05		< .001			
Content_dysfluent_unresolved (Intercept)	GLMM:NB	0.00	0.00–0.01	−14.13	< .001		1.67	0.79	.32
Content_dysfluent_resolved		1.4	0.67–2.95	0.89		.373			

Note. CI = confidence interval; ICC = intraclass correlation coefficient; GLMM = generalized linear mixed-effects model; NB = negative binomial.

between the composite variable *Content-fluent-aligned* and the overall clinical measure of spontaneous speech, which is a score combining measures of both spontaneous speech information content and fluency.

Discussion

This study examined the putative compensatory role of gestures by investigating their distribution, temporal overlap with speech, and correlation with language measures in people with BA and WA. Our first research question concerned the quantity of content gestures. In this regard, at a descriptive level, results showed that *non-content* gestures made up the greatest proportion of gestures across all groups (see the work of Kong et al., 2015). Since beat gestures do not carry the thought content that content gestures as defined here do, they cannot compensate for lost content. Moreover, as also seen from the gesture distribution pattern in Figure 3, the proportion of descriptive gestures relative to other gesture types in the controls was almost twice that in the PWWA and 3 times that in the PWBA. Clearly, PWA did not compensate for lost descriptive content through an increase in descriptive gestures relative to other types of gestures. When testing for significant differences in content-bearing gestures in the between-groups comparisons, there were no significant group differences in either descriptive or metaphorical gestures, reinforcing the absence of a compensatory effect for these types of content gestures. On the other hand, both PWBA and PWWA produced significantly more referential gestures than control participants. These gestures, as defined here, serve to identify or localize a referent but provide no descriptive information about it. A natural hypothesis to explain this pattern could be that referential gestures differ from descriptive ones in the associated hand movements, which in the case of the latter need to symbolically depict or match the different visual and spatial information of the objects or events referenced. An index-finger referential pointing gesture, by contrast, is simple and uniform, allowing to identify a referent without the need for symbolizing descriptive properties, and they may rely less on semantic association and object recall, which is often impaired in PWA (Fonseca et al., 2019).

Table 5. Correlational analysis.

Variable	WAB measure	Correlation	*p* value
Content gesture	Aphasia quotient (AQ)	$r = .177$	.274
Content gesture	Comprehension	$r = -.201$	.218
Content-fluent	Spontaneous speech fluency	$r = .428$	.006
Referential_fluent	Spontaneous speech fluency	$r = .407$	.010
Content_fluent_aligned	Spontaneous speech score	$r = .384$	.016

Note. WAB = Western Aphasia Battery.

A quantitative increase in a certain type of gesture, however, does not imply a compensation effect. Firstly, at least in the WA group, the referential gestures also contained more anomalies (see further below). Secondly, the crucial question is the relationship of the overproduced referential gestures to coproduced speech, which was our second specific research question. Results in this respect strikingly showed that referential gestures in the clinical group were predominantly produced when speech was *fluent*, as opposed to when speech was dysfluent or absent. In short, though quantitatively more produced, even referential (as well as the descriptive) gestures were still largely used in integration with speech rather than functioning by themselves: Temporally, content gestures and speech go hand in hand. Moreover, when they were coproduced with fluent speech, the content of gesture was significantly aligned with that of speech, further supporting the perspective of speech–gesture integration by Graziano and Gullberg (2018), rather than a compensatory effect as defined here. This result is contrary to previous findings that gesture production in PWA was largely associated with occurrences of lexical retrieval problems relative to fluent speech production (Kistner et al., 2019; Lanyon & Rose, 2009). The diverging results could be explained by the fact that different gesture types were analyzed in these other studies. For example, Lanyon and Rose (2009) had grouped all gesture types in their analysis, and Kistner et al. (2019) looked specifically at a broad range of semantically rich gestures comprising iconic, metaphoric, pantomime, air writing, and numbers, whereas the gestures of interest of this study exclusively concerned content gestures of the referential, descriptive, and metaphoric types, disregarding the examination of other gesture types regarding their temporal relationship with co-occurring speech. With regard to the small amount of content gestures that were coproduced with dysfluencies, there was, furthermore, no significant difference as to whether the dysfluencies were resolved or not, calling into question the assumption that content is carried in gestures and drives its subsequent lexical expression. This result is in line with earlier studies showing no significant evidence for the facilitation role of gesture in lexical retrieval in PWA (Kong et al., 2018; Lanyon & Rose, 2009).

While PWWA and PWBA did not differ between them in the production of referential gestures, when taking speech fluency into account, PWWA produced more referential gestures that were coproduced with fluent speech than PWBA. As WA is defined by greater speech fluency relative to BA, this result may suggest a connection between fluency and gesture production, with more fluent speech pulling along more (referential) gestures, which was also confirmed by the correlational results to be discussed below. This gesture profile of PWWA speaks to other aspects of their speech profile. Thus, as has been documented earlier (Manning & Franklin, 2016), individuals with fluent aphasia had more instances of pronouns than those with nonfluent aphasia in discourse production. Although this did not form part of our formal analysis, we equally observed that PWWA tended to overuse pronouns and spatiotemporal adjuncts (i.e., *here, there*), which were often accompanied by referential gestures during their speech production. Interestingly, Göksun et al. (2015) found that brain lesions to the left superior temporal gyrus (which often result in WA) correlated with greater production of gestures that express spatial information (i.e., path gestures).

Importantly, referential gestures used by PWWA were also more likely to be anomalous than those used by PWBA, suggesting a loosening of the neurotypical frame of reference. Put differently, PWWA overproduce ambiguous referential expressions accompanied by gestures, indicating a loss of cognitive control over the referential meaning intended to be expressed. In keeping with early investigations showing that PWWA tended to produce a higher ratio of referentially unclear gestures (Cicone et al., 1979; Glosser et al., 1986), this study moreover reconfirms that the anomalous referential gestures parallel the anomalous speech profile of PWWA, which has previously been found to be characterized by a high rate of empty phrases and referential errors (such as unclear pronouns; Nicholas et al., 1985). Therefore, gestures here were unlikely to be compensatory in that they did not tend to be clearer when speech itself was anomalous. We speculate that the difference in the production of referentially anomalous speech and gestures in PWWA also may reflect differences in cognitive function between the two aphasia groups, with PWWA tending to be cognitively more impaired than PWBA (Ardila & Rubio-Bruno, 2018; Baldo et al., 2005, 2010). This specifically includes deficits in semantic cognition in PWWA in both verbal and nonverbal semantic tasks (Ogar et al., 2011; Robson et al., 2012), which appears to have an impact on gesture production (Cocks et al., 2013; Hogrefe et al., 2012; Kong et al., 2015; Kroenke et al., 2013).

Regarding gestures other than content ones, both PWBA and PWWA produced more emblems than controls, and PWWA employed more beat gestures and pantomimes than controls. Crucially, however, beat gestures do not carry content; emblems carry conventionalized, primarily interactional content; and both emblems and pantomimes tend to be produced without speech even in neurotypical people. Pantomime moreover represents a special category of gesture whose production has been suggested to rely on different resources than cospeech gestures (Bartolo et al., 2003). Overproduction of emblems and pantomimes therefore may well suggest some compensation effect, just not a compensation for a loss of the kind of content conveyed in speech. Previous research has already highlighted the potential of pantomimes to compensate for verbal limitations in PWA (Rose et al., 2017; van Nispen et al., 2017), and Rose et al. (2017) specifically pointed to their communicative effectiveness, which was best achieved when pantomimes co-occurred with speech.

Our third specific research question concerned correlations between the frequency of content gesture production and measures of aphasia severity, comprehension ability, and speech fluency. In this regard, we found that the more fluent PWA were, the more they tended to use content and referential gestures, which further coheres with our finding that PWWA overproduced referential gestures with fluent speech compared to PWBA. Therefore, we did not find evidence for a compensation effect in the sense that nonfluent aphasia is associated with more use of content gestures (Sekine et al., 2013). It has been previously found that people with nonfluent aphasia were more likely than other types of aphasia to produce meaning-laden (e.g., deictic and iconic) gestures in story-retell tasks (Sekine et al., 2013; Sekine & Rose, 2013). However, it is noteworthy that in both of these studies, the meaning-laden gestures were defined to cover a wide range of gestures, with some (i.e., emblems, pantomime) not fitting with our classification, which may explain the differences in results. While we did not find a correlation between aphasia severity and gesture production, a closer inspection of the gesture and clinical profile of PWA suggested that two participants from the BA group who produced the least amounts of gestures also had the most severe aphasia. Among all PWA, one participant from the BA group with the lowest number of gestures produced the least utterances, and one from WA group with the most gestures had produced the greatest number of utterances. Together, these exceptional cases seem to suggest a potential link between gesture production and language capacities, manifested either in the amount of speech or in the clinical measure of aphasia severity.

Our results have both clinical and foundational implications. With regard to the former, our overall results suggest that gestures have no compensatory effect for difficulties of language, which suggests recentering therapeutic efforts on language as the driver of gesture rather than vice versa. Nonetheless, it is also clear from the results that for functional and communicative purposes, PWA benefit from gestures, and some are easier for them than others, emblems and referential gestures among them. With regard to foundational implications, our results throw into question the view that, if language fails as a provider of thought content, that content could be expected to transpire in another modality. Instead, the pattern reported here is consistent with the view that content gestures are indeed verbal in nature, carrying *verbal* content, with the implication that when language fails to provide such content, it is not likely to appear elsewhere. Crucially, this is not to diminish other communicative functions of gestures rather than that of substituting content, which the sketch model of gesture and speech production (de Ruiter, 2000) particularly stresses. Indeed, the result of overproduction of emblems in PWA in our study also points in this direction. That said, it remains striking that even a group virtually defined by their speech *dysfluency* (i.e., PWBA) still tended to coproduce gesture with episodes of *fluent* speech, with the content of their gestures and speech *aligning*. If thought and language are "not the same thing" (Fedorenko & Varley, 2016), then our results suggest that it is still not likely to see the content of such thought outside of the domain of language. The pattern found here is more consistent with the opposite view (Baldo et al., 2005; Hinzen & Sheehan, 2015) that language is an effective reasoning tool or mode of thought, such that the loss of this tool also impacts on what thought content there is to be conveyed.

Limitations and Future Directions

A number of limitations need to be acknowledged. First, we have taken into consideration the quality of videos and the visibility of arm and hand gestures for each participant we selected in this study. However, there are videos in the AphasiaBank database that are not suitable for studying gestures, and future contributors of multimodal data to public databases should take this factor into account. Second, additional information about the severity of limb apraxia was not available. There are inconsistent findings regarding the potential influence of limb apraxia on spontaneous gesture production. A prior study by Borod et al. (1989) revealed positive correlations between praxis ability and gesture use. Hogrefe et al. (2012) showed that the severity of limb apraxia had an impact on the ability to produce clear gestures that are easily comprehensible for the listeners. Still, there are other studies finding no significant negative influence of limb apraxia on gesture production (Marshall et al., 2012; Rose & Douglas, 2003). A third limitation of the study was the unavailability of data concerning verbal and nonverbal semantic skills of PWA, which would contribute to our interpretation of gesture production profile of PWA. Moreover, given the importance of intact semantic processing for an adequate use of gesture and speech and for the integration of both communicative channels (Hogrefe et al., 2012), speech therapists for aphasia should consider the potential impact of semantic processing skills of a patient on speech and gesture production, and include this knowledge during diagnosis and treatment planning.

Research investigating the temporal overlap between spontaneous gesture and speech in PWA remains limited and could benefit from an expansion of methods. Thus, we highlight two future directions. On the one hand, future studies investigating the gestural behavior of PWA could benefit from using a more naturalistic discourse-based method such as free conversations, as findings obtained from this context could more reliably reflect the true gestural capacity of PWA. Previous evidence already suggests that gestures elicited from test conditions were qualitatively and quantitatively different from gesture production in spontaneous speech (Cocks et al., 2007; Rose & Douglas, 2003; Lanyon & Rose, 2009). In this study, the use of free speech elicited by structured interviews enabled observation of gesture and speech produced by PWA in a relatively natural conversational context, avoiding potential confounds in experimental test conditions (i.e., using deictic gestures in the presence of picture stimuli or mimicking actions in animation clips). On the other hand, this study provides new evidence for the temporal alignment between content gestures and language in a broad and still relatively coarse-grained sense. An important line of future investigation would be to investigate whether gestures more specifically align with grammatical units of the accompanying speech such as adjuncts, predicates, and referential noun phrases, or rather show some independence from such structuring principles driven by grammar.

Data Availability Statement

The data underlying the results presented in this study are available from the AphasiaBank database (https://aphasia.talkbank.org/), which is password protected. Readers can refer to the AphasiaBank webpage in order to have access to the data.

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