



## Discussion forum

# The dorsal language pathways in stuttering: Response to commentary

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In a commentary on our recent paper (Kronfeld-Duenias, Amir, Ezrati-Vinacour, Civier, & Ben-Shachar, 2016a), Neef, Anwender, and Friederici (2017) “question the view that an impairment of the dorsal language pathway [in adults who stutter] implicates aspects of motor processes rather than aspects of language processing”. Here, we defend the interpretation of our data in terms of impaired motor control aspects of speech production in adults who stutter (AWS). We argue that the bilateral nature of our findings, in the context of prior studies, supports the interpretation in terms of motor (or sensorimotor) control aspects of speech production, rather than in terms of syntactic or semantic processing. We further report on behavioral measurements from the same sample of AWS, showing that their performance on lexical access, verbal working-memory and syntactic processing tasks is comparable to that of the control participants. We conclude that tract differences warrant interpretation in a wider context, both in terms of the overall pattern of implicated tracts within a study, and by considering recurring patterns in the relevant clinical population across studies.

The main critique raised by Neef et al. (2017) alludes to our interpretation of the differences found in the dorsal language tracts of 15 AWS, compared to 19 adults who do not stutter. In their letter, the authors suggested that the “Included structures [AF<sub>long</sub> and AF<sub>ant</sub>] do not exclusively mediate motor functions, but are primarily implicated in higher-level

language processing”. Indeed, a difference in a specific white matter tract does not translate exclusively to a single functional mechanism. This is because white matter tracts, particularly the large, long-range fiber bundles that are well sampled with diffusion MRI, are unlikely to subservise a single function. Such pathways convey signals between distant cortical territories, in a spatial pattern that resembles the way communication cables are laid between continents: thin branches converge into a thick bundle which traverses the bulk of the distance (the submarine communication cable), then diverging again into thin branches. Diffusivity parameters (such as fractional anisotropy, FA) are more reliable in the core, thick segment of the long-range bundle, and least reliable in the thin branches, particularly near gray matter, where a small “bump” on a nearly isotropic orientation distribution function can sway the tract in one direction or another (Ben-Shachar, Dougherty, & Wandell, 2007; Jones, 2008). For this reason, our analysis samples the core of the tract and avoids its extremities, but this may come at the cost of functional specificity.

For example, properties of the left AF<sub>long</sub> have been associated with syntactic processing (Skeide, Brauer, & Friederici, 2016; Wilson et al., 2011), but the same pathway has also been associated with phonological awareness (e.g., Yeatman et al., 2011; Vandermosten et al., 2012; Saygin et al., 2013, and more). These findings are not in conflict with each other, because the

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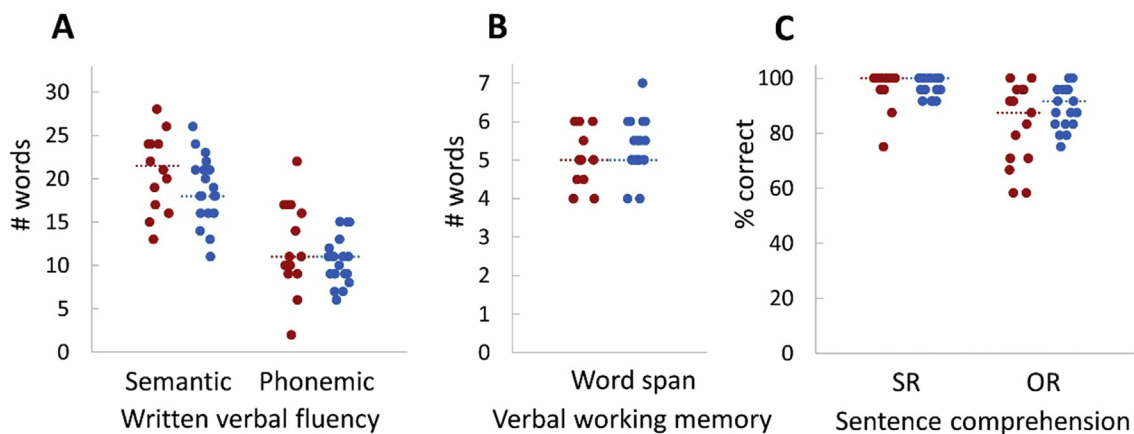
left AF<sub>long</sub> is a major “highway” connecting perisylvian regions in the temporal and frontal lobes. Therefore, it is likely to carry signals relevant for more than a single type of processing. With these limitations in mind, we argue that some interpretations can still be proposed, and others can be rendered less plausible, for a specific pattern of affected tracts, particularly in the context of prior findings within the relevant population.

Several aspects of the results led us to interpret our findings in terms of impaired motor control aspects of speech production in AWS, rather than in terms of impaired syntactic or semantic processing. First, we found bilateral differences in the dorsal pathways of AWS. This pattern fits better with recent findings that sensory motor transformations involved in speech production occur bilaterally (Cogan et al., 2014; see also Silbert, Honey, Simony, Poeppel, & Hasson, 2014). Syntactic processing, on the other hand, has been associated selectively with FA of the left dorsal tracts. Wilson et al. (2011), for example, reported that “only the left SLF/Arcuate predicted [syntactic] comprehension ... and production... The right SLF/Arcuate did not predict either syntactic comprehension or production” (Wilson et al., 2011, p. 3). Along the same lines, Skeide et al. (2016) reasoned that “Right hemisphere homologs of the left-hemispheric syntax sensitive regions were not analyzed ... as they were, to the best of our knowledge, never specifically associated with the processing of complex syntactic information...” (Skeide et al., 2016, p. 2136). The bilateral differences in the dorsal pathways of AWS thus fit better with an impairment in motor control aspects of speech production (Hickok, 2012; Saur et al., 2008). This interpretation of the data is also in good agreement with the notion that stuttering

involves altered forward models and/or feedback control (Civier, Tasko, & Guenther, 2010; Max, Guenther, Gracco, Ghash, & Wallace, 2004), two motor control mechanisms subserved by the left and right fronto-parieto-temporal networks (Golfinopoulos, Tourville, & Guenther, 2010; Guenther & Hickok, 2015).

Recall also that our findings were restricted to the dorsal stream. We did not detect any differences between AWS and controls within the analyzed ventral pathways (i.e., the uncinate fasciculus and the inferior fronto-occipital fasciculus, IFOF). Prior studies support the hypothesis that these ventral pathways are involved in mapping sound to meaning (Catani & Bambini, 2014; Hickok & Poeppel, 2004, 2007; Rauschecker & Scott, 2009). Specifically, tract properties of the uncinate fasciculus were associated with semantic processing in patients with primary progressive aphasia (Catani et al., 2013), lesion-volume and FA within the left IFOF correlate significantly with performance of semantic tasks in stroke and tumor patients (Almairac, Herbet, Moritz-Gasser, de Champfleury, & Duffau, 2015; Han et al., 2013; Kümmerer et al., 2013) and individual differences in the left IFOF of healthy young adults correlate with measures of semantic control (Nugiel, Alm, & Olson, 2016). Lacking a significant difference in the IFOF and uncinate, our findings do not line up with an interpretation as an impairment in abstract, semantic aspects of language processing in AWS.

Finally, to provide a more complete picture of higher level language abilities in our sample of AWS and controls, we examined behavioral data that were collected from the same participants on several language tasks (Fig. 1). Participants



**Fig. 1** – Performance of AWS and controls on language tests. Individual data points (circles) and group medians (dotted lines) are shown for adults who stutter (red) and controls (blue). The data were collected in the original sample (see Kronfeld-Duenias et al., 2016a for biographical and clinical characteristics). Data are shown for three language tests: (A) Written verbal fluency (number of words written in a minute for a given semantic category or opening sound), (B) Verbal working memory (number of spoken words in the longest sequence reproduced correctly in writing) and (C) Sentence comprehension (% correct responses to comprehension questions on spoken sentences that incorporated a subject relative (SR) or object relative (OR) clause, in center embedded or right branching position). All tests were conducted in Hebrew, the participants' native language. Group differences between AWS and controls were assessed using two-tailed, non-parametric, Mann–Whitney *U* tests. No significant group differences were observed in any of these measures ( $p > .1$ ). RTs in the sentence comprehension task were similar as well across the two groups (SR: Mann–Whitney  $U = 109$ ,  $p > .2$ , two-tailed; OR: Mann–Whitney  $U = 131$ ,  $p > .7$ , two-tailed). Further, the difference between the two syntactic conditions did not differ significantly between the groups in either accuracy (SR–OR: Mann–Whitney  $U = 99.5$ ,  $p > .1$ , two-tailed) or RT (OR–SR: Mann–Whitney  $U = 135$ ,  $p > .8$  two-tailed). Non-parametric statistics were used to account for non-normality in the accuracy scores. Similar  $p$  values were attained using  $t$ -tests in all other measures.

completed a battery of language tests (performed within about 2 months of the scan in most subjects; median of 20 days between scan and behavioral battery), including measures of written verbal fluency (modified from Kavé, 2005), verbal working memory (the Word Span subset from FriGvi battery in its written version; Gvion & Friedmann, 2008) and syntactic processing (comprehension of spoken object and subject relative clauses, adapted from the Battery for Assessment of Syntactic Abilities in Children [BAMBI] Zika Meguvana; Friedmann & Novogrodsky, 2002, 2004). Across these tasks, we were unable to identify any significant group differences in performance (the distributions of individual responses are shown in Fig. 1, for statistics see caption). Thus, there is no indication in the current sample of AWS for a deficit in lexical-semantic processing, verbal working memory, or syntactic processing.

The interpretation we offered in our paper is in no way definitive. As we acknowledge in the paper: “Our findings do not rule out the possibility that stuttering may involve a language deficit”. Still, we argue that an interpretation in terms of impaired motor control of speech production is compatible with the general pattern of bilateral dorsal differences reported in our study, as well as with prior findings in persistent developmental stuttering, showing bilateral differences in the AF/SLF of adults (Cieslak, Ingham, Ingham, & Grafton, 2015; Connally, Ward, Howell, & Watkins, 2014; Watkins, Smith, Davis, & Howell, 2008) and young children (Chang, Zhu, Choo, & Angstadt, 2015) who stutter, bilateral differences in the cerebro-spinal tract (CST) (Cai et al., 2014; Connally et al., 2014) and bilateral differences in the frontal aslant tract (Kronfeld-Duenias, Amir, Ezrati-Vinacour, Civier, & Ben-Shachar, 2016b). This interpretation is also compatible with theoretical accounts of persistent developmental stuttering in terms of altered feedback-based motor control systems (Civier et al., 2010; Max et al., 2004). As a whole, these findings portray a consistent picture of persistent developmental stuttering in adults, highlighting tracts involved in motor control aspects of speech production.

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