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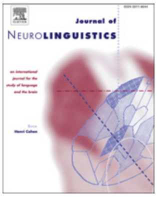

The processing of syntactic islands – An fMRI study

Ken Ramshøj Christensen[a,b,*], Johannes Kizach[b], Anne Mette Nyvad[b]

[a] Center for Functionally Integrative Neuroscience, Aarhus University Hospital, Denmark
[b] Department of Aesthetics and Communication, Aarhus University, Denmark

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ABSTRACT

The aim of this study was to investigate whether LIFG activation was sensitive to increases in syntactic working memory load triggered by multiple extractions from an embedded clause, so-called island violations, and whether there was any difference between argument and adjunct extraction. Event-related fMRI ($n = 30$) was used to measure the cortical effects of the differences in acceptability between ungrammatical sentences and three types of *wh*-movement in Danish: short movement (to the front of an embedded clause), long movement (to the beginning of the matrix clause), and movement across another *wh*-phrase. The neural activation in LIFG was predicted to correlate negatively with the level of acceptability. Ungrammatical sentences were predicted to engage LIFG, potentially overlapping with the effects of acceptability. The behavioral results replicated the findings from an earlier study showing that acceptability correlates negatively with demands on syntactic working memory. Short movement is more acceptable than long movement, which is more acceptable than movement across another *wh*-phrase. Contrary to prediction, the imaging data showed no significant difference between long movement and movement across another *wh*-phrase, while both induced a significant increase in activation in LIFG compared to short movement. It is argued that the clause itself, rather than movement as such, is an important factor. Movement out of an embedded clause increases syntactic complexity, which in turn increases neural activation. Short movement per se is not complex enough to have a significant effect on the BOLD signal. There was

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[*] Corresponding author. Department of Aesthetics and Communication, Aarhus University, Jens Chr. Skous Vej 4, DK-8000 Aarhus C, Denmark. Tel.: +45 8716 2567.
E-mail address: Ken@cfin.dk (K.R. Christensen).

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no effect of ungrammaticality, but this absence is argued to be due to the nature of the anomaly. The activation in LIFG correlated with the crossing of a clause boundary, not with increases in working memory load or decreases in acceptability due to island violations.

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1. Introduction

This paper investigates the neural substrate of syntactic processing by focusing on a specific syntactic operation, namely syntactic movement, a central concept in the theory of generative syntax used to account for word order variation (e.g., Chomsky, 1995; Radford, 2004). Syntactic movement has been and still is the subject of intense studies in psycho- and neurolinguistic research (e.g., Ben-Shachar, Palti, & Grodzinsky, 2004; Kluender & Kutas, 1993; Santi & Grodzinsky, 2007). According to Nicol and Swinney (1989), movement is computed on-line, and it is one of the foremost contributors to the perceptual complexity of sentences in the performance of healthy subjects (Fodor, Bever, & Garrett, 1974; Neville, Nicol, Barss, Forster, & Garrett, 1991). In addition, numerous lesion-based studies on syntactic movement have indicated that certain kinds of syntactic movement pose specific comprehension difficulties to agrammatic Broca's aphasics (e.g., Bastaanse, Bouma, & Post, 2009; Grodzinsky, 2000; Zurif, Swinney, Prather, Solomon, & Bushell, 1993).

In the field psycholinguistics there is a longstanding debate on the nature of constraints on word order variation and syntactic movement (e.g., Clifton & Frazier, 1989; Hofmeister & Sag, 2010; Sprouse, Wagers, & Phillips, 2012). In particular, there is a discussion on *wh*-extraction from embedded clauses. In (1) below, there is Short movement; it is short because the target of the movement (i.e., the position where the *wh*-expression occurs) is inside the same clause as the source (or canonical) position, indicated with '__'. In (2), there is Long movement because the target position is outside the embedded clause containing the source position. Long movement is known to increase processing cost (Christensen, Kizach, & Nyvad, 2012; Fanselow & Frisch, 2006; Phillips, Kazanina, & Abada, 2005). In (3), there are two simultaneous *wh*-movements, and one movement applies Across the target position of the other, resulting in a highly degraded (indicated with '??') or ungrammatical sentence (indicated with '*') (Rizzi, 1990:4). (For this reason, embedded *wh*-questions, illustrated with square-brackets [] in (1)–(3), are traditionally referred to as *wh*-islands; the second *wh*-element is marooned on the island, unable to escape.)

(1) a. I know [which problem she can solve __ in this way]. (Short)
b. I know [how she can solve this problem __].
(2) a. Which problem do you think [she can solve __ in this way]? (Long)
b. How do you think [she can solve this problem __]?
(3) a. ??Which problem do you wonder [how she can solve __ __]? (Across)
b. *How do you wonder [which problem she can solve __ __]?

Hofmeister and Sag (2010) show that the acceptability of so-called island violations, such as (3), is gradable and sensitive to a variety of syntactic factors, such as locality and the distance between filler (the moved element) and gap (the canonical or source position). They argue that such *wh*-island effects are not due to grammatical constraints but rather to working memory (WM) constraints on processing. However, Sprouse et al. (2012) tested this hypothesis by examining potential interactions between individual general memory capacity and acceptability judgments of a variety of island violations, and found no correlation. They therefore concluded that island phenomena must be due to violations of competence-given restrictions on grammar, rather than limited general processing resource capacity. Christensen et al. (2012) present data from a behavioral study on sentences such as (1)–(3) where they used a 5-scale acceptability judgment task. The results showed that Short is significantly more acceptable than Long which in turn is significantly more acceptable than Across. Christensen et al.

(2012) interpret this graded acceptability and observed selective learning/priming effects (with acceptability going up over time) as supporting the processing approach referring to syntactic (not general) WM.

Furthermore, it is widely held that there is an asymmetry in the acceptability of movement Across an argument (Arg), such as the object *which problem* in (3a), and moving an adjunct (Adj), the adverbial *how* in (3b); Across (Arg) is more acceptable than Across (Adj). This asymmetry is typically taken to be due to a grammatical locality constraint (e.g., Poole, 2011:249f; Radford, 2004:225; Rizzi, 1990:4; Vikner, 1995). However, Christensen et al. (2012) found no asymmetry in Across, but they did find one in Long movement, which followed from processing: The fronted *wh*-object in (2a) is temporarily interpreted as the object of the matrix verb *think* and subsequently reanalyzed as the object of the embedded verb; the fronted *wh*-adjunct *how* in (2b), on the other hand, is incompatible with such a reading which gives rise to a temporary anomaly, which in turn reduces the overall acceptability (Fanselow & Frisch, 2006).

In this study, we applied a neuroimaging perspective using fMRI in order to measure the neural correlates of the differences in acceptability between (i) movement to the front of an embedded clause (Short), (ii) movement out of an embedded clause (Long), and (iii) movement across another *wh*-phrase (Across), as well as the putative argument/adjunct asymmetry in movement from a *wh*-island in Danish.

Numerous studies have found that syntactic processing engages the left inferior frontal gyrus (LIFG), for example structural ambiguity and garden-path phenomena, clausal embedding, and word order variation or syntactic movement (see Christensen, 2010; Christensen & Wallentin, 2011, and references cited there). Santi and Grodzinsky (2007) and Makuuchi, Bahlmann, Anwander, and Friederici (2009) present data supporting the idea that LIFG supports domain-specific WM resources for syntactic computation (syntactic movement and center-embedding, respectively), not domain-general WM. However, Ben-Shachar et al. (2004) investigated embedded *wh*-questions in Hebrew and found no significant difference between subject and object extraction in LIFG. Several other studies have also reported no differential LIFG effect when comparing subject and object extraction (Cooke et al., 2001; Fiebach, Vos, & Friederici, 2001; Indefrey, Haagort, Herzog, Seitz, & Brown, 2001). See Caplan et al. (2001) for discussion.

In addition to the effect in LIFG, syntactic complexities, such as structural ambiguity, center-embedding, and word order variation, have also been found to engage the posterior superior temporal cortex (pSTC) (see Christensen, 2010, and works cited there). Both LIFG and pSTC are regions traditionally considered to be classical language areas. However, many neurolinguistic studies on syntax have also found involvement of other areas, in particular, premotor cortex in the precentral gyrus (PrCG) (Christensen, 2009, 2010; Christensen & Wallentin, 2011; Hanakawa et al., 2002; see Christensen, 2008; Stowe, Haverkort, & Zwarts, 2005, for overviews). Finally, premotor cortex (BA 6) has been found to be involved in structure-dependent computation, such as sequential ordering of hierarchical structures in working memory (Hanakawa et al., 2002; Marshuetz, 2005).

The processing of semantic and pragmatic anomalies has also been associated with increased activation in LIFG (e.g., Baumgaertner, Weiller, & Büchel, 2002; Cardillo, Aydelott, Matthews, & Devlin, 2004; Christensen & Wallentin, 2011; Embick, Marantz, Miyashita, O'Neil, & Sakai, 2000; Hagoort, Hald, Bastiaansen, & Petersson, 2004; Ni et al., 2000; Suzuki & Sakai, 2003). It has been argued that LIFG can be divided into three functional subdivisions, such that the posterior superior part, the pars opercularis (BA 44) is involved in syntactic processing, whereas the anterior inferior pars triangularis (BA 45) and pars orbitalis (BA 47) are involved in thematic integration and lexical semantic processing, respectively (e.g., Bookheimer, 2002; Dapretto & Bookheimer, 1999; Fiebach, Schlesewsky, Lohmann, von Cramon, & Friederici, 2005; Friederici, 2002; Newman, Just, Keller, Roth, & Carpenter, 2003; but see Lindenberg, Fangerau, & Seitz, 2007). Christensen and Wallentin (2011) found that complexity (processing) and anomaly (error) are distinct but interact and overlap in LIFG.

Based on the literature, the following predictions were made. If LIFG is sensitive either to an incremental increase in WM or to an incremental decrease in acceptability, the BOLD response in LIFG would be predicted to be the inverse of the acceptability hierarchy reported by Christensen et al. (2012), i.e., Across > Long > Short (where > means 'induces higher activation than'). Furthermore, there should be a contrast between long movement of an argument and an adjunct, namely, Long (Adj > Arg), given that argument movement is significantly more acceptable than adjunct movement.

Independently, unambiguously anomalous sentences are predicted to engage LIFG, potentially overlapping with the complexity effect.

2. Methods

2.1. Participants

A total of 33 people participated in the experiment. Three were excluded from the analysis; one due to missing image files, one reported to have been pushing the response repeatedly across events, thus introducing motor response confounds, and one turned out to be narcoleptic. The remaining 30 participants were all right-handed native speakers of Danish with no prior history of brain injury or abnormalities (13 men, 17 women, mean age 23.8 years, range 18–34, std. 3.9).

2.2. Materials

The stimulus set was identical to the one used in experiment 1 in Christensen et al. (2012) (except we use only one baseline here). It consisted of 8 conditions with 16 tokens in each (a total of 128 sentences), see Table 1. In all the tokens, subject and verb of the matrix clause were *hun* 'she' and *ved* 'knows'. The set of verbs used in the embedded clauses in all conditions was: *bruge* 'use', *bygge* 'build', *drikke* 'drink', *finde* 'find', *høre* 'hear', *købe* 'buy', *leje* 'rent', *lære* 'learn', *læse* 'read', *låne* 'borrow', *prøve* 'try', *smage* 'taste', *skrive* 'write', *spille* 'play', *spise* 'eat', and *sælge*, 'sell'. The baseline used as control for syntactic movement was a verb-initial *yes/no*-question. There were three types of movement (Short, Long, and Across) and two types of extracted *wh*-elements (the argument (Arg) *hvad* 'what' and the adjunct (Adj) *hvor* 'where'), resulting in six movement conditions. In addition, there was an Anomaly condition consisting of ungrammatical sentences where the two (Arg and Adj) *wh*-elements were immediately adjacent at the beginning of the embedded clause and as such 'compete' for the same structural position. The Anomaly condition was included as control for ungrammaticality, to test whether the Across type of movement triggered a neural response different from unambiguously ungrammatical sentences.

Table 1
Stimulus conditions and examples.

Condition	Example
Base	Ved hun godt at man kan leje noget dér? *Knows she well that one can rent something there?* "Does she know that you can rent something there?"
Short (Arg)	Ved hun godt hvad man kan leje dér? *Knows she well what one can rent there?* "Does she know what you can rent there?"
Short (Adj)	Ved hun godt hvor man kan leje noget? *Knows she well where one can rent something?* "Does she know where you can rent something?"
Long (Arg)	Hvad ved hun godt at man kan leje dér? *What knows she well that one can rent there?* "What does she know that you can rent there?"
Long (Adj)	Hvor ved hun godt at man kan leje noget? *Where knows she well that one can rent something?* "Where does she know that you can rent something?"
Across (Arg)	Hvad ved hun godt hvor man kan leje? *What knows she well where one can rent?* "What does she know where you can rent?"
Across (Adj)	Hvor ved hun godt hvad man kan leje? *Where knows she well what one can rent?* "Where does she know what you can rent?"
Anomaly	*Ved hun godt hvor hvad man kan leje? *Knows she well where what one can rent?* "Does she know where what you can rent?"

The choice of using bare (single word) *wh*-elements (*hvad* 'what' and *hvor* 'where') instead of complex (multi word) *wh*-phrases (e.g., *which car* and *where in Denmark*) was motivated by three considerations. One, we wanted to keep the stimuli as simple as possible to keep processing load and task difficulty at a minimum. Two, since Christensen et al. (2012) found the same acceptability pattern for bare and complex *wh*-expressions in the Long and Across types of movement, it seems reasonable to use the simplest form. Three, results from processing of semantically less complex sentences should be generalizable to semantically more complex sentences with the same overall syntactic structure, but not necessarily vice versa (Clifton, Fanselow, & Frazier, 2006).

2.3. *Procedure*

Participants read the sentences in the scanner via a mirror mounted on the head coil. Stimuli were projected one sentence at a time onto a screen using a video projector standing outside the scanner room. The task was an acceptability judgment task in which participants responded with a button press (right index finger for "OK" and right middle finger for "Not OK"). Participants were instructed to answer as fast and accurately as they could and to rely solely on their own intuition rather than on what they expected to be standard or correct language. In order to separate linguistic processing from motor output, each participant only judged half of the sentences in each condition, see Fig. 1. The sequence was randomized such that all sentences were judged by half of the participants; if participant one judged, for example, sentences 1, 4, 5, 7, etc., but not 2, 3, 6, and 8, then participant 2 would do it the other way around and judge 2, 3, 6, and 8, but not 1, 4, 5, and 7.

The order of sentences was pseudo-randomized across participants. Stimuli were presented and responses (answer and response time, RT) collected on a PC using Cogent 2000 (The Cogent 2000 Team, Functional Imaging Laboratory and Institute of Cognitive Neuroscience, UCL, London) running in Matlab 7.9 (Mathworks Inc., Sherborn, MA, USA).

2.4. *MR acquisition*

Functional MR images were acquired on a Siemens TrioTim 3 T system using a standard head coil. Scans were performed using an echo planar imaging sequence with FA = 90°, TE = 30 ms, TR = 2000 ms. A total of approximately 545 volumes were acquired for each participant. Each volume consisted of 37 axial slices covering the entire brain (slice thickness = 3 mm, spacing = 3 mm, FOV = 134.4*134.4 mm, matrix = 64*64 voxels).

2.5. *MR data analysis*

The fMRI data was analyzed using SPM8 (Wellcome Department of Imaging Neuroscience, University College London). The imaging data were realigned for motion correction, normalized (reslicing the voxels to 2 × 2 × 2 mm), and smoothed (8 mm FWHM). All events were modeled using the standard hemodynamic response function of SPM8, plus the time and dispersion derivatives for

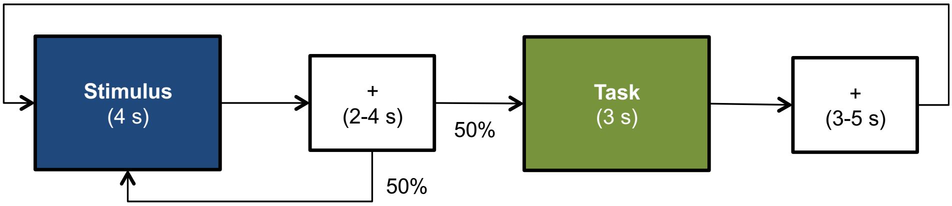

Fig. 1. Experimental design. The stimulus was presented non-incrementally, one sentence a time. Each sentence was visible for 2 s. After a 2–4 s randomized interval with a fixation cross on the screen, there was 50% chance of getting a judgment task and 50% chance of getting the next stimulus sentence. In case of the judgment task, the next stimulus sentence would follow after a randomized interval (with a fixation cross) of 3–5 s. This randomization of task occurrence and inter-stimulus intervals ensured that the brain activation due to motor response was orthogonal to the changes in brain activation triggered by linguistic processing.

each condition. The model was estimated for each participant using a general linear model (128s high-pass filter and AR(1) modeling of serial correlation), before being submitted to a second level, random-effect analysis. This was conducted as a one-way whole-brain ANOVA in SPM8 (independence and equal variance not assumed). The voxel-level threshold of significance was set to $p < 0.05$, FWE corrected for multiple comparisons.

3. Results

3.1. Behavioral data

The behavioral data were analyzed using a generalized linear mixed-effects model, including both fixed factors and participants and tokens as random factors (cf. Baayen, 2008; Baayen, Davidson, & Bates, 2008). A model was fitted to *answer* as the dependent (binary) variable using R for Windows (R Development Core Team, 2009) and the lme4 package for R (Bates, Maechler, & Bolker, 2011). Contrastive coding was used to get pair-wise comparisons of means for adjacent conditions (MASS package, Venables & Ripley, 2002). Only four of the pair-wise contrasts revealed significant differences, namely, Short (Adj) > Long (Arg), Long (Arg) > Long (Adj), Long (Adj) > Across (Arg), and Across (Adj) > Anomaly, see Fig. 2. The pattern that emerges is thus identical to the one reported in Christensen et al. (2012), where the same stimuli were judged by 60 subjects on a 5-point grammaticality scale. There was no significant difference between Base, Short (Arg), and Short (Adj), and no significant difference between Across (Arg) and Across (Adj).

Unlike Christensen et al. (2012), we found no significant syntactic priming or repetition effects (correlations between order of presentation and acceptability). We included *order* as a fixed effect and an interaction term was added between *condition* and *order* in the generalized linear mixed-effects model, but neither showed any significant effects ($p > 0.112$), and both *order* and the interaction term were consequently removed from the final model.

3.2. fMRI data

A one-way ANOVA revealed the following significant effects ($p < 0.05$, corrected for multiple comparisons using Family-Wise Error, FWE), see Table 2. The main effect of *wh*-movement out of an

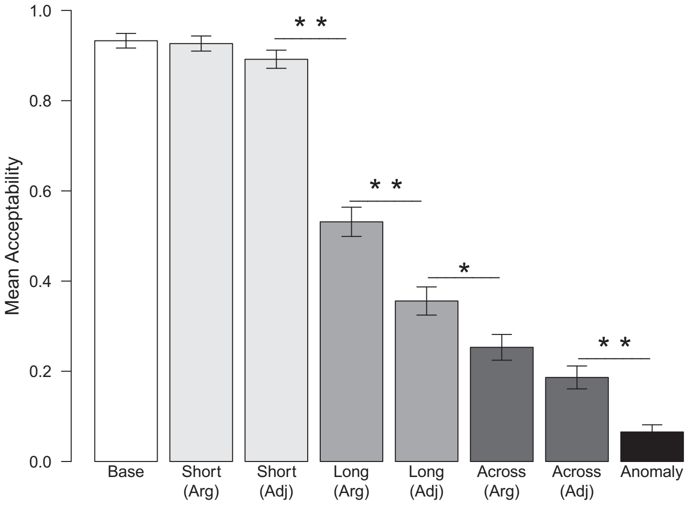

Fig. 2. Bar plot of acceptability (mean across subjects and tokens) by condition. Error bars: ±SE. Asterisks (*) indicate significant differences ($p < 0.05$). Sequentially Bonferroni-corrected for multiple comparisons (Holm, 1979), $^{*}p < 0.05$, $^{**}p < 0.001$.

Table 2
Region and Brodmann Area (BA) investigated using WFU (Wake Forest University School of Medicine) Pickatlas (Maldjian et al., 2004, 2003) for SPM (region according to the AAL atlas, Tzourio-Mazoyer et al., 2002, BA according to the Talairach Space, Talairach & Tournoux, 1988). Cluster size is given in voxels (2 × 2 × 2 mm); coordinates refer to the MNI space.

Contrast	Cluster size	*P* (FWE)	*T*	Coordinates	Region
MAIN Move-Out	2138	0.000	7.97	−46, 12, 22	LIFG-oper
		0.000	7.48	−46, 2, 48	LPrCG (BA 6)
		0.000	6.81	−56, 20, 12	LIFG-tri (BA 45)
	919	0.000	7.17	−6, 10, 58	LSMA
		0.000	6.54	−4, 8, 68	LSMA
		0.000	5.76	−4, 18, 48	LSMA (BA 8)
	102	0.000	5.81	−50, −34, −2	LMTG
		0.007	5.17	−58, −26, −2	LMTG (BA 22)
	12	0.014	5.01	36, 26, 0	R-Insula
Long > Short	378	0.000	6.61	−46, 12, 22	LIFG-oper
		0.002	5.56	−56, 20, 12	LIFG-tri (BA 45)
		0.011	5.22	−56, 26, 20	LIFG-tri
	215	0.000	6.18	−44, 2, 48	LPrCG (BA 6)
	230	0.001	5.89	−6, 12, 56	LSMA
		0.010	5.23	6, 20, 46	RSMA (BA 32)
		0.013	5.17	−8, 10, 70	LSMA
	154	0.001	5.67	−50, 32, −6	LIFG-orb
		0.010	5.23	−52, 20, 0	LIFG-tri (BA 47)
	34	0.002	5.55	−50, −34, −4	LMTG
	3	0.030	4.96	−2, 2, 68	LSMA
Across > Short	205	0.000	6.60	−46, 2, 50	LPrCG (BA 6)
	301	0.000	6.31	−4, 8, 60	LSMA
		0.000	5.95	0, 4, 66	LSMA
	331	0.000	6.29	−46, 12, 22	LIFG-oper
		0.000	6.13	−56, 20, 12	LIFG-tri (BA 45)
		0.032	4.95	−56, 22, 20	LIFG-tri (BA 45)
	23	0.015	5.14	−48, 32, −6	LIFG-orb
	19	0.016	5.12	−52, −32, −2	LMTG (BA 21)
		0.018	5.09	−58, −26, −2	LMTG (BA 22)
	3	0.023	5.03	10, 16, 52	RSMA
	3	0.029	4.97	8, 20, 58	RSMA
MAIN Arg > Adj	5	0.020	5.07	−54, −22, 4	LSTG
	7	0.021	5.05	42, −8, 64	RPrCG
	1	0.031	4.96	38, −14, 62	RPrCG
	1	0.033	4.94	32, −20, 64	RPrCG (BA 6)
Short (Arg > Adj)	4	0.006	5.35	−36, −22, 20	L-insula (BA 13)
	1	0.025	4.88	32, −20, 64	RPrCG (BA 6)
	3	0.039	4.78	−54, −22, 4	LSTG

embedded *wh*-question to the front of the matrix clause, Move-Out ({Long, Across} > {Base, Short}), showed relative increased activation in four clusters (see Fig. 3): cluster one was a very large activation cluster in the frontal lobe, stretching from the orbital part of the left inferior frontal gyrus (LIFG) to the dorsolateral part of the left premotor cortex (left precentral gyrus, LPrCG); cluster two was a large bilateral activation cluster in the supplementary motor area (SMA); cluster three was in the middle part of the left middle temporal gyrus (LMTG); finally, cluster four was located in the right insula. Both the Long > Short contrast and the Across > Short contrast showed large activation clusters in LIFG, LPrCG, and SMA, and a small cluster in the middle LMTG. There was also a small but significant main effect of Argument vs. Adjunct, which, surprisingly, turned out to be driven solely by the Arg > Adj contrast within Short movement (i.e., Short (Arg > Adj)). None of the other meaningful contrasts revealed any significant results; that is, there was no effect of Short movement (Short > Base), no difference between Across and Long (Across > Long), and no effect of Anomaly vs. any of the other conditions (Anomaly > Base/Short/Long/Across).

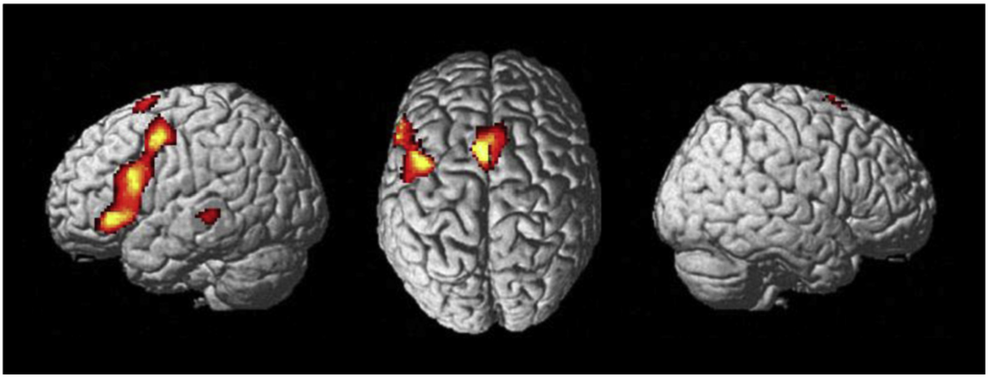

Fig. 3. Surface rendering of the Move-Out effect ($p < 0.05$ FWE).

As is clear from Fig. 4, all conditions increased the activation level relative to the overall mean in the three local maxima of the large MAIN Move-Out cluster.

Due to the anatomically specific hypothesis about the crucial involvement of LIFG, a region of interest (ROI) analysis was applied using the WFU (Wake Forest University School of Medicine) Pick-atlas (Maldjian, Laurienti, & Burdette, 2004; Maldjian, Laurienti, Kraft, & Burdette, 2003) referencing in the AAL atlas (Tzourio-Mazoyer et al., 2002). The ROI comprised pars opercularis, pars triangularis, and pars orbitalis. However, restricting the search to this ROI, revealed no additional results.

Given the hypothesis about a functional subdivision of LIFG into the anterior pars triangularis (or BA 45) and the posterior pars opercularis (or BA 44), primarily involved in syntactic processing and thematic/semantic integration, respectively, we applied a cluster analysis of the three major LIFG activations using WFU Pickatlas. The results are summarized in Table 3. In all three clusters, both subparts of LIFG were involved.

4. Discussion

The aim of this study was to investigate whether LIFG activation was sensitive to increases in syntactic working memory load triggered by multiple extractions from en embedded clause, so-called island violations, and whether there was any difference between argument and adjunct extraction. The behavioral results showed the same pattern as the one reported in Christensen et al. (2012), where it was argued that the pattern follows from a processing account, specifically from Gibson's (1998) Dependency Locality Theory. The pattern is also predicted by Hawkins (1994, 2004), where the complexity of a dependency is measured as the sum of all intervening nodes between a filler and its gap. Short involves only one dependency and contains less intervening material between the filler and

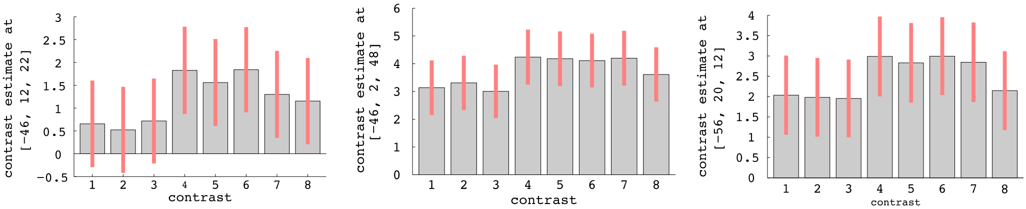

Fig. 4. Bar plots of the average signal change in the BOLD response in the three local maxima of the large cluster (2138 voxels) of the main Move-Out contrast, see Table 2 (error bars indicate 90% confidence level). From left to right: LIFG pars opercularis, LPrCG (BA 6), LIFG pars triangularis (BA 45).

Table 3

Cluster analyses of LIFG activations in the three contrasts showing significant changes in activation (cf. Table 2). Numbers denote number of voxels (subparts of the major activation clusters) in each of the cortical regions. BA according to the Talairach Space, both accessed using WFU Pickatlas.

Contrast	Long > Short		Across > Short		Move-Out	
Cluster size	378 voxels		331 voxels		2138 voxels	
BA 44	22	5.8%	43	13.0%	73	3.4%
BA 45	46	12.2%	60	18.1%	136	6.4%
LIFG-oper	138	36.5%	173	52.3%	370	17.3%
LIFG-tri	212	56.1%	152	45.9%	756	35.4%

the gap than Long. Across is even more complex since it involves two dependencies both adding to the complexity (Hawkins, 2004). This predicts the Short > Long > Across pattern, and the remaining difference between Long (arg) and Long (adj) is most likely due to matrix verb compatibility and factivity, as demonstrated in Christensen et al. (2012).

Christensen et al. (2012) reported syntactic priming/repetition effects in Long and Across in the sense that acceptability increased over time. Judgments from a binary scale will exhibit less variation than data from a 5-point scale, and the absence of learning effects in the present study could be due to this inherent difference between the scales (Weskott & Fanselow, 2011:253). The fact that the same overall behavioral pattern arises both in this study and in Christensen et al. (2012) supports the idea that, despite the lesser variation, a binary scale is as good as a 5-point scale to represent the gradience of the judgment data as argued in Weskott and Fanselow (2011).

Since the behavioral results were identical to those reported by Christensen et al. (2012), the neuroimaging data were expected to match the prediction that the neural response would be the inverse of the acceptability hierarchy reported by Christensen et al. (2012). However, that was not the case.

The neuroimaging results showed no difference between Base and Short and no difference between Long and Across. Both Long and Across showed more activation than Short and Base in four regions in the left hemisphere, namely, inferior frontal (LIFG), premotor (LPrCG), supplementary motor (LSMA), and posterior middle temporal cortex (LMTG) (see Table 2). The involvement of these regions in syntactic computation is well-known. Therefore one might speculate whether this neural pattern reflects differences in syntactic complexity. However, the brain response does not correlate with syntactic complexity as measured in Christensen et al. (2012) (reflected in differences in acceptability), who did not take into account that Long and Across applied across a clause boundary. The results are fully compatible with the intuition that a clause boundary is a significant factor; both Long and Across are movements that cross a clause boundary and both increase neural activation, whereas Short and Base did not involve operations across a clause boundary and showed less activation than Long and Across.

The clause (or Complementizer Phrase, CP) is a phase, a syntactic processing unit or workspace, which is impenetrable from outside operations, such as agreement and *wh*-question formation (Chomsky, 2001, 2005). Therefore, movement out of a clause is cyclic; it applies via a left-peripheral specifier, Spec-CP, which will then contain a phonologically silent but semantically and syntactically interpretable and operational copy of the moved element. The evidence supporting successive cyclic *wh*-movement via intermediate Spec-CP positions is abundant, from cross-linguistic studies (for brief overviews, see Poole, 2011:166–168; Radford, 2004:394–401) as well as from psycholinguistic experiments (Gibson & Warren, 2004; Marinis, Roberts, Felser, & Clahsen, 2005). In terms of the number of syntactic phases straddled by movement, Long and Across are equally complex; Long movement moves from the base-position to the embedded Spec-CP and from there to the front of matrix clause; Across involves movement of one *wh*-element to the embedded Spec-CP and movement of another *wh*-element to the matrix Spec-CP. One might speculate that Across applies via an additional specifier, licensed as Last Resort, perhaps an instance of an occurrence feature (Chomsky, 2005:18). Such a position is independently required for long extraction from embedded clauses headed by the interrogative complementizer *om* ‘if’, cf. (4); the *wh*-operator *hvad* ‘what’ is not allowed to occupy the embedded Spec-CP, (4a), but it is allowed to ‘stop-over’ on the way to the matrix Spec-CP, (4b):

(4)a *Ved hun ikke [$_{CP}$ hvad om Lars har fundet __]
Knows she not if John has found
‘*Does she not know what if John has found?’
b Hvad ved hun ikke [$_{CP}$ __ om Lars har fundet __]?
What knows she not if John has found
‘What does she not know if John has found?’

From the existence of an extra Spec-CP licensed as Last Resort (providing the embedded clause with an ‘escape hatch’), it would follow that Across is more complex than Long because it involves more syntactic movement. The lack of contrast in the BOLD signal could be due to neutralization. Changing phase is the primary source of the activation and the additional Short movement step is not sufficiently demanding to trigger a significant change in the BOLD signal. This is supported by the fact that there is no significant difference between Short and Base; Short movement is not complex enough to trigger an increase in activation large enough to be detectable with fMRI (at least not with the current setup).

The hypothesis that Short movement in itself does not trigger a large enough cortical response, is also supported by the absence of a contrast between Short (Arg) and Short (Adj); furthermore, other studies have also found no Subject/Object asymmetry in Short movement (Ben-Shachar et al., 2004; Cooke et al., 2001; Fiebach et al., 2001; Indefrey et al., 2001). However, other studies do report a Short (Obj > Subj) effect, and the variation in the literature could be taken to suggest that other factors than Short movement as such are at play, influencing processing cost.

It is important to emphasize that the phase account and the processing account of Christensen et al. (2012) are fully compatible. Crossing a phase boundary also entails increasing working memory load. A phase is considered to be not only a syntactic processing domain, but also a semantic unit, namely, a proposition (Chomsky, 2001, 2005) so it is predicted to be taxing on memory under any account. (Shetreet, Friedmann, & Hadar, 2009, report increased LIFG activation for relative clauses compared to semantically equivalent small (verbless) clauses in Hebrew, which shows that the activation goes with the structure, not the semantics.) Since language is compositional, not only the number of words and morphemes, but also the proposition itself adds to WM load. In the experiments in Christensen et al. (2012), however, adding the clause or phase as a factor would not alter the results in any way. The increase in WM demands was correlated with the crossing of the clause/phase boundary. Both Long and Across crossed the clause boundary giving rise to increased processing difficulty and decreased acceptability, which is the exact same effect predicted by the processing account. It is conceivable that the subtle but significant difference in processing and working memory load is too small to be captured with fMRI, at least with the current experimental design.

A final point concerns the absence of an observed anomaly effect. Some researchers have found syntactic anomalies to engage LIFG (e.g., Embick et al., 2000; Ni et al., 2000; Suzuki & Sakai, 2003), whereas other researchers have not (Humphries, Love, Swinney, & Hickok, 2005; Kuperberg et al., 2003). Kuperberg et al. (2003) actually found relative deactivation in LIFG, but increased parietal activation, triggered by subject-verb agreement errors, e.g., **We couldn’t sleep at night because the baby would cries*. (It should be noted that this variation could, at least partially, be due to the relatively small number of participants in these studies, ranging from 8 to 14). A meta-study on neuroimaging of syntax provides evidence that hierarchical structure is processed in LIFG, whereas transitional probability is processed in operculum (Friederici, 2004; see also Makuuchi et al., 2009). This could be taken to suggest that a syntactic violation has to be hierarchical in nature (such as subcategorization errors or phrase structure violations) in order to trigger LIFG. Support for this comes from a neuroimaging study of second language learning. Musso et al. (2003) found that learning real, structure-dependent syntactic rules, activated LIFG, whereas learning made-up, structure-independent rules (hence, violations of fundamental principles of human language), did not. (Structure-independent rules include, for example, inversion of declarative word order in interrogatives, and placement of sentential negation after word number three; no known human language has rules like these.)

In the present study, the anomaly consisted of two adjacent *wh*-elements (*hvor hvad* ‘where what’) in a sense competing for the same structural position. As only one *wh*-element can be attached in this position, the sentence has no overall syntactic structure. Sprouse (2007) has argued that only grammatical sentences have full syntactic interpretations; the idea is that an ungrammatical string cannot be generated by the grammar and as such cannot be assigned a full syntactic interpretation (though it may have partial interpretations). If *Doubly-filled Spec-CP is principally underivable (and hence, has no full syntactic interpretation), then the violation is not hierarchical, and hence, this type of syntactic violation would not be predicted to increase activation in LIFG. Support for this comes from the study by Christensen et al. (2012) under the assumption that learning effects are only possible with grammatical strings. Christensen et al. (2012) found learning effects for Long and Across, which were given degraded acceptability, but not for downright ungrammatical *Doubly-filled Spec-CP sentences (acceptability at floor throughout) and not for fully grammatical sentences with Short movement (acceptability at ceiling). Furthermore, Humphries et al. (2005) contrasted grammatical sentences with pseudo-random sequences of words with sentence prosody, i.e., strings that can not be generated by the grammar, and found no LIFG activation but an effect in the left anterior superior temporal cortex.

5. Conclusions

The present experiment was based on the following predictions: (i) The level of activation in LIFG should be linearly correlated with the level of acceptability if LIFG were sensitive to relative increases in WM. And if so, the relative pattern would be expected to be the inverse of the acceptability ranking of Christensen et al. (2012), such that the hierarchy in terms of activation level would be Across > Long > Short. Furthermore, there should be a significant Long (Adj > Arg) effect, because argument movement is significantly more acceptable than adjunct movement. (ii) Independently of (i), unambiguously anomalous sentences were predicted to increase activation in LIFG, potentially overlapping with the effect in (i).

The behavioral data completely replicates the results of Christensen et al. (2012); there was no difference in acceptability between Short and Base. The rest of the contrasts in type were significant resulting in the following acceptability hierarchy: Short > Long > Across > Anomaly. There was also a significant Long (Arg > Adj) contrast. Based on the behavioral pattern, we expected prediction (i) to be borne out. However, it was not. Instead we observed an effect of moving out (Move-Out) of the embedded clause: {Across, Long} > Short. This effect is compatible with a model that emphasizes the role of the clause as a processing unit, a phase in the terminology of minimalist syntax. The lack of contrast between Across and Long could be attributed to the fact that there was no effect of Short movement. Across consists of one instance of Long and one instance of Short; the latter did not trigger an effect large enough to significantly increase the level of activation. The absence of an effect of the anomalous sentences was attributed to the nature of the anomaly; the string is ungrammatical, and as such cannot be derived by the grammar. As a result, it is not a hierarchical anomaly; the anomaly effects normally reported to trigger LIFG are subcategorization errors, which are inherently hierarchical. This interpretation of the role of LIFG is compatible with the more or less uncontroversial assumption that LIFG is involved in the processing of hierarchical complexities in language.

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