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Action verbs drive motor activity in adolescents but not in children

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ABSTRACT

In adults, grip force has reliably been used to investigate motor simulation evoked by linguistic action, suggesting that motor phenomena are linked to semantic action. The parietal and frontal lobes and their connexions are essential neural structures for pragmatic aspects of hand semantic action. In this perspective, the aim of the study was to determine the extent to which two groups of children and adolescents, classically characterized by degree of axonal myelination in fronto-parietal circuits, monitored the occurrence of nouns and manual action verbs presented auditorily while holding a grip force sensor. Differential effects of grip force were seen only in the adolescents when monitoring action verbs. Interestingly, weaker effects of grip force were modulated by noun targets only in the younger children, revealing that the ability to profit from a full semantic representation of verbs is not clearly established in the younger children. Grip force modulation was observed as early as 300 ms post target onset and peaked at the 500–750 ms window of observation for both groups. These group differences are in line with the motor simulation difficulties seen in younger children. The results may also indicate that degree of grip force in response to specific linguistic categories parallels the maturation of the parietal-frontal circuits, including the anterior intra-parietal area which plays a determining role in semantic aspects of hand action.

1. Introduction

Morphological changes during brain development are non-linear, as brain areas mature at different rates (Toga et al., 2006; Richardson et al., 2018). In the first years of life, the brain is highly dependent on afferences; gradually, it becomes active in processing incoming sensory information. The neurofunctional basis for this transition is the maturational state of the parietal and frontal lobes and the state of connections between these structures. The forebrain is also crucially involved in decision and filter processes, the analysis of a context preceding action, attention, working memory, motor activity, and language (Fuster, 2002; Casey et al., 2011; Siegel et al., 2011). The parietal lobe is a central structure in the processing of somatosensory and spatial information (Avillac et al., 2005), mathematical knowledge (Dehaene et al., 1996), as well as the neural substrate for embodied action of the hand (Sakata et al., 1997).

The relationship between the parietal and frontal lobes is also essential in how we interact with the outside world, both socially and physically. Motor action is an important component of this interaction, and the hand plays a specific role in our dealings with the environment. An influential proposal to account for this interaction was Mishkin and Ungerleider's (1982) characterization of the dorsal occipital-parietal and ventral occipital-temporal pathways in the treatment of visual afferent activity—the *where* and *what* pathways in primates. A translation of that theory involving prehension was proposed by Goodale and Milner (1992); it specified separate visual pathways for perception and action, with the dorsal pathway involved in perception leading to action, while the identification of objects is the province of the ventral pathway. More recently, Jeannerod and Jacob (2005) developed a pragmatic theory of hand action, which now included the purpose of action—taking into account the semantic configuration of the hand as a function of what the subject wants to do. These semantic operations are claimed to be under the control of the parietal cortex. In this framework, cognition is the result of the interaction between the brain's sensory and motor systems (for a review, see Gallivan and Culham, 2015). Grasping an object, for example, reveals a complex interplay between motor processes, sensory information about the object's features, and action-related aims or semantics (see also Fuster, 2003, 2009).

Most studies of hand configuration have examined kinetic aspects such as transport and reaching (e.g., Paulignan et al., 1997). Grip force

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plays an important role in the semantic configuration of the hand (Lemon, 1981; Muir and Lemon, 1983; Lemon et al., 1986). It is now understood that there is a privileged link between the anterior intraparietal area (AIP), a tertiary cortex area, and the hand motor area—making the former structure an essential component in the pragmatic view of hand semantic action (Sakata and Taira, 1994; Murata et al., 2000, 2016).

One way of looking at the semantic and configurational aspects of hand action is to investigate motor simulation evoked by linguistic stimuli. In a study with adults, Frak et al. (2010) showed that grip force is modulated by action verb terms. Subjects were asked to monitor the occurrence of either verb or noun stimuli of similar imageability, while holding a grip force sensor. An increase in grip force was observed between 260 and 340 ms following the presentation of action verbs. These results with the measurement of grip force were replicated using noun and verb stimuli in isolation or embedded in sentences (Aravena et al., 2012, 2014; Nazir et al., 2017; Da Silva et al., 2018) and can be taken as evidence that motor phenomena are linked to semantic recognition—expressed as an involuntary motor outflow resulting from language-induced simulation of action. Recently, it was shown, using Event-Related Potentials, that there exists a correlation between semantic discrimination and grip force modulation (Juárez et al., 2019).

Consequently, the parietal lobe is a multisensory relay with afference from diverse structures such as Wernicke's area (Burks et al., 2017). It is also closely connected via BA6 to M1 and to Broca's area (Hickok and Poeppel, 2007; Catani et al., 2012). This complex network can be understood as the neuroanatomical substrate for the modulation of hand kinetics by language (Willems and Hagoort, 2007; Desai et al., 2011; Tomasino and Rumiati, 2014; Rizzolatti and Sinigaglia, 2016; van Dam and Desai, 2016). This linguistic induction of motor resonance circuits was originally described in the context of action and object observation (Grèzes et al., 2003; Rizzolatti & Craighero, 2004).

In adults, it has been proposed that verb stimuli influence modulation of force by triggering the simulation of a manual gesture (Frak et al., 2010). It is also the case that from the age of 11 children find it easier to incorporate motor simulation in the performance of a skill (for a review, see Spruijt et al., 2015). Interestingly, it has been shown that the parietal lobe displays morphological maturity by 13 years of age (Gogtay et al., 2004), especially in the degree of myelination and cortical thickness (Toga et al., 2006) — a main maturation process. In contrast, the frontal lobes are far from being fully developed. Yet, in both childhood and adolescence, there are similar levels of attention span, control of inhibition and executive function with respect to simple tasks (Capilla et al., 2004). These results highlight the likelihood of a structural basis for motor simulation. In this perspective, the modulation in grip force in a simple verb monitoring task in children and adolescents would help towards elucidating the involvement of parietal structures on the fronto-parietal circuits in driving semantic action.

Efforts have been made to clarify how verbs are treated in early development. In a fMRI study looking at neural activation patterns during passive verb and adjective listening in preschool children, the primary motor system was recruited for verbs but not for adjectives. The authors could only observe frontal activation but concluded that the motor regions are associated with the effectors in question (James & Maouene, 2009). In an eye-tracking study, listening to a sentence containing a verb interfered with action perception in toddlers aged 12 months but had a facilitating influence at 24 months for verbs that are already in the productive repertoire (Gampe & Daum, 2014). More recently, Antognini and Daum (2019) investigated the suppression of the mu rhythm in toddlers to determine the involvement of the sensorimotor system in language and action. They found a suppression of the mu rhythm with verb and action presentations but not with pseudoverb items. Taken together, the results of these studies suggest that verb perception activates the motor system in the developing brain, manifesting the embodied nature of language learning.

The AIP is intimately connected to language (such as Broca's area) and to motor brain regions. In humans, this structure reaches maturity in adolescence and plays an essential part in the simulation of hand gestures. If the modulation of M1 by semantic processing is well established, the extent to which the simulation of hand action is also well grounded in children remains to be determined (see also Cayol et al., in this special issue). As the simulation of hand gestures is compounded by experience with one's environment and the maturation of the AIP, it is expected that the modulation of grip force, — a well-studied index of the simulation of hand gestures (e.g., Frak et al., 2010) — to the presentation of hand action verbs will differ between younger children and adolescents. In addition, the semantic charge of the linguistic message is known to modulate M1 activity (Guan et al., 2013). In turn, M1 covaries with the grip force response (Ward et al., 2007). In this perspective, it was expected that adolescents exhibit a stronger grip force than younger children when processing hand action verbs.

An analysis is also conducted that takes into consideration the time course of grip force. This was inspired by the neurophysiological model of sentence comprehension proposed by Friederici (2002) which has become the basis for analyzing grip force modulation arising from language stimulation (see Da Silva et al., 2018). This analysis will reveal the extent to which the expression of grip force following linguistic processes is similar in both children and adolescents.

2. Methods

2.1. Participants

Two groups of participants, all right-handed (Edinburgh scale cut-off score = 40; Oldfield, 1971), native speakers of Canadian French, and attending primary or secondary school in the Laval (Quebec) school district, took part in the study. The younger group was initially made up of 15 children (6 girls, 9 boys; mean age = 7.4 ± 1.6, range = 6–10 years) and the older group included 14 teenagers (9 girls, 5 boys; mean age = 14.9 ± 1.5, range = 13–17 years). The subjects had no history of hearing problems or psychiatric or neurological disorders. Their parents or guardians gave written and informed consent and the study was approved by the UQAM institutional ethics committee.

2.2. Stimuli

A list of 35 nouns was constructed that served as background, non-target words, and five verbs related to hand action were also selected: *prendre* 'take', *pincer* 'pinch', *découper* 'cut out', *colorier* 'color', and *gratter* 'scratch'. The stimuli, taken from Frak et al. (2010), were bi- or tri-syllabic words and had been controlled for frequency of occurrence following New et al.'s (2001) method. The selected words were spoken by an adult male speaker of Canadian French and recorded on a digital voice recorder (Olympus DS-50). The mean spoken duration of the stimuli was 684 ± 98 ms. The noun stimuli are presented in Appendix 1 and the verbs in Appendix 2.

Forty lists of verbal stimuli were constructed by randomly ordering the 35 background words. A non-action target noun was inserted into 20 lists and a target action verb into 20 other lists. The target words differed between lists and were repeated between 10 and 12 times within a list. Thus, each list consisted of 35 background stimuli and 10 to 12 repetitions of a target word. The order of words in each list was pseudo-random and two target words never occurred in succession. Each subject was presented with four lists including a total of 22 target verbs and 22 target nouns. Audio-editing software (Audacity) was used to generate and construct the lists of stimuli from the WAV files. The duration of the lists of stimuli varied between 75 and 80 s each.

2.3. Equipment

The grip force sensor was a 1.8 cm thick uniaxial (x axis) unit with two 5 cm washers on each side; it was rated for pressure up to 1.0 kg.

Amplitude of the output signal was 1.0 mV / V ± 10%. The linearity error and hysteresis were 0.02% relative to the entire scale. The sensor was connected to a Honeywell DV10L amplifier linked to an acquisition card (Measurement Computing USB-1608GX) with a data transfer rate of 1 kHz. Observations were processed using a Toshiba Satellite laptop (C-850-P0011) with Windows 8. The stimuli were delivered as WAV sound files from the laptop's left channel via headphones (Sony MDR-7502). The right channel was used for triggers synchronized with the onset of each stimulus. Data were processed using DASYLab 11.0 software (Measurement Systems Ltd.), and filtered at 15 Hz with fourth zero, low-pass Butterworth, and 50 Hz notch filter.

2.4. Procedure

Subjects, wearing headphones, were tested one at a time in a quiet setting, at a desk and on a chair adjusted for the proper height, with their right forearm resting on a foam mat. They were asked to hold a grip force sensor with a precision grip (thumb, index and middle fingers), with the fifth metatarsus, but not the sensor, resting on the mat. Subjects were initially guided, with eyes closed, to apply a stable 1.5 N pressure on the sensor, following Nazir et al.'s (2017) method. The participants were given a short training session and the experiment proper started once pressure on the sensor was stable and sound was set at a comfortable level. The children's understanding of the meaning of the target words was ascertained by asking them to either mimic or explain target words (e.g., *star, take*) when they were given at the beginning of each of the four lists. They were asked to keep track of the occurrence of the target word and tell the experimenter how many they had heard at the end of the presentation. Two-minute breaks were given between lists to ensure that the children were comfortable. The duration of the experiment was about 20 min. Fig. 1 shows the experimental setup.

2.5. Data analysis

The data analysis included GFM in response to target words only. Because grip force can vary between trials, the GFM data were normalized following Nazir et al.'s (2017) procedure. The window of interest for each target was 1100 ms—a baseline period of 200 ms preceding the occurrence of a target, and the period from 100 to 1000 ms after. Mean GFM during baseline was subtracted from mean GFM during target word presentation—although this method made it possible to obtain a negative value, it did not mean an absence of grip force.

Data were not retained if GFM exceeded 100 mN/100 ms. Consequently, two participants from each group were excluded from the study because 30% or more of the recorded measurements included excessive force variation.

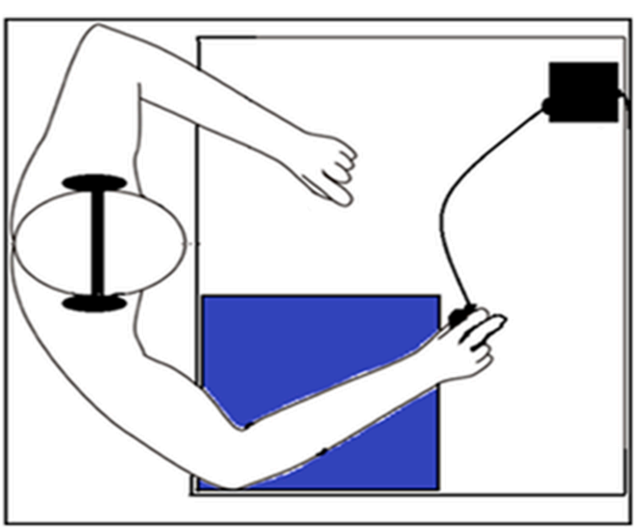

Fig. 1. Schematic representation of experimental set-up.

3. Results

A Group (children, adolescents) X Occurrence (baseline, presentation of stimulus) X Stimulus (action verbs, nouns) ANOVA, with repeated measures on the last two factors was conducted to determine whether grip force can be modified by linguistic action stimuli, and whether the two groups of participants differed in the processing of that information. The analyses of interest revealed a Group effect ($F = 6.573$; $df = (1, 19)$; $p = 0.019$; $\eta 2 = 0.257$) showing that the two groups differed in GFM. There was also a main effect of Occurrence ($F = 12.044$; $df = (1, 19)$; $p = 0.003$; $\eta 2 = 0.388$), showing that GFM increased after the presentation of the target stimuli. A Group X Stimulus interaction ($F = 6.02$; $df = (1, 19)$; $p = 0.024$; $\eta 2 = 0.241$) indicated that the two groups behaved differently with respect to the nature (verb, noun) of the stimuli. A post hoc Fisher's Least Significant Difference (LSD) test revealed that the adolescents exerted a stronger GFM in response to verb targets than the children did ($p = 0.002$). Fig. 2 shows the modulation of grip force for the two groups of subjects when monitoring action verb and noun targets.

An ANOVA was also conducted on Group X Time (with four time periods considered: 100–299 ms, 300–499 ms, 500–749 ms, and 750–1000 ms) X Stimulus, with repeated measures on the last two factors, to determine when the linguistic stimuli influenced grip force. The results of interest revealed a main effect of GROUP ($F = 6.167$; $df = (1,19)$; $p = 0.023$; $\eta 2 = 0.245$), and a main effect of Time ($F = 17.014$; $df = (2.084, 39.594)$; $p < 0.001$; $\eta 2 = 0.472$). Mauchly's test indicated that the assumption of sphericity had been violated ($\chi 2(5) = 19.4$; $p = 0.002$); the degrees of freedom were therefore corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.695$). There were significant interactions showing that GFM was not expressed in the same way between the two groups over the classes of stimuli (Group X Stimulus: $F = 5.542$; $df = (1, 19)$; $p = 0.029$; $\eta 2 = 0.226$), showing more GFM on the part of the older group for verbs ($p = 0.003$) but no difference between groups for noun targets ($p = 0.76$). There were also interactions over time (Group X Time: $F = 4.163$; $df = (3, 57)$; $p = 0.01$; $\eta 2 = 0.180$) indicating that grip force is most pronounced in the 500–749 ms ($p = 0.02$) and 750–1000 ms windows ($p = 0.014$) for the older group. There was also a Stimulus X Time interaction ($F = 4{,}417$; $df = (1.542, 29.292)$; $p = 0.29$; $\eta 2 = 0.189$). Here again, Mauchly's test indicated that the assumption of sphericity had been violated ($\chi 2(5) = 29.2$, $p = 0.002$), and the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.514$).

Three additional significant results were also revealed in the LSD post hoc analyses. In adolescents, GFM was stronger for verb targets,

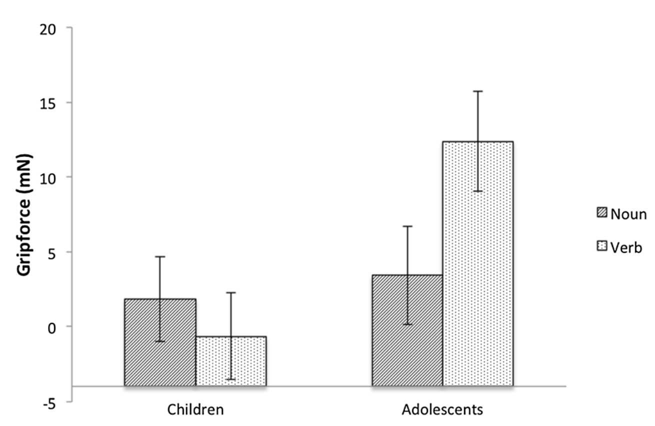

Fig. 2. Grip force modulation (Bars represent standard error) by children and adolescents monitoring the occurrence of target nouns and action verbs.

relative to younger children, from 300 ms on (second time window: $p = 0.014$; third window: $p = 0.001$; fourth window: $p = 0.003$). Interestingly, post hoc LSD analyses showed that GFM for noun targets were stronger than for verb targets in children only (third time window: $p = 0.027$; fourth window: $p = 0.034$), an unexpected result. Finally, GFM was stronger for verbs in adolescents in the third time window, as revealed by post LSD analysis ($p < 0.01$). Fig. 3 shows the modulation of grip force over the first 1000 ms following the presentation of target stimuli in both groups.

4. Discussion

The main objective of this study was to determine the extent to which grip force is modulated in children and adolescents, in response to the semantic content of linguistic stimuli. The main results of interest were that the adolescent group showed a clear differentiation in grip force between the noun and action verb targets while the younger group showed no such disparity. Grip force for verbs was different between the two groups while it was similar for the noun stimuli.

This dissociation in grip force when monitoring action verbs could be taken as evidence for the influence of maturation of the parietal lobe on parietal-frontal circuits in semantic aspects of hand action. It also suggests that word class exerts a distinctive impact on motor systems and that maturation of the neural substrate also plays an important role. Recently, we have also shown that there is a correlation between prefrontal P200 activation and grip force modulation in a verb monitoring task, with adult subjects (Juárez et al., 2019) further suggesting the influence of semantic content on action.

Activation in prefrontal areas was also noted by Pulvermüller et al. (1999), who showed a difference in early P2 amplitude between nouns and verbs, suggesting that semantic content can be discriminated as early as 200 ms following stimulus onset. The modulation of grip force by language is currently understood as reflecting the expression of the semantic content of linguistic information. A general conclusion from studies with auditory (e.g., Frak et al., 2010; Da Silva et al., 2018; Juárez et al., 2019) and visual (Blampain et al., 2018) material is that semantic content includes the simulation of motor action (see Liberman and Mattingly, 1985). In the present study, there is an increase in grip force from baseline to the presentation of stimuli, and again with action verb stimuli but only for older subjects. The time course of grip force also revealed that the lexical-semantic processes and the simulation of hand action verbs starting at the second window of analysis, seen in adolescents only, is congruent with a one-step model that does not preclude both lexical and post-lexical operations. This suggests a more complex view than the classic approach — where the motor structures have been

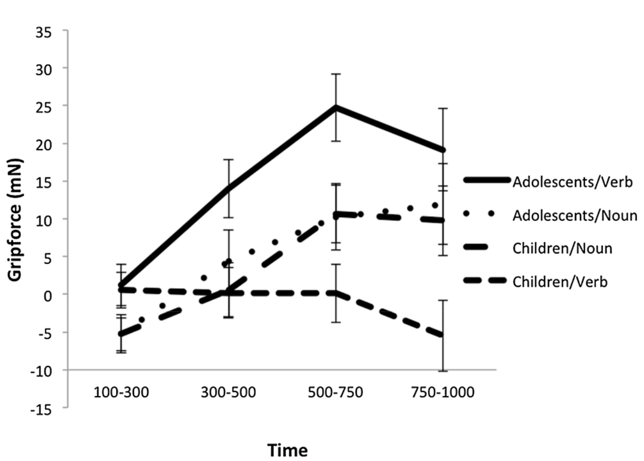

Fig. 3. Grip force modulation (Bars represent standard error) over time by children and adolescents when monitoring the occurrence of target nouns and action verbs.

considered to be functional in language comprehension only if activated during the postlexical process (see also Aravena et al., 2014). A strong argument for M1 activation by language is that words that activate that area of the brain (as expressed by grip force) cease to do so when they occur in negative form, as shown in the study by Aravena et al. (2012). Activation, in the view of Liberman and Mattingly (1985), is the motor simulation necessary to understand the meaning of gestures. Simulation is thus an integral part of sensory and motor processes (see also Prinz, 1997).

It should be noted that the exertion of grip force was not confined to verbs of hand action only but also to nouns such as *storm*, *cliff* and *canyon*—although to a significantly lesser degree. Interestingly, both groups were uniform in their response to noun stimuli, displaying grip force with moderate strength. It is the case that all words can elicit grip force to varying degrees (Dreyer and Pulvermüller, 2018). Interestingly, motor affordance is evident in children for objects but not for verbs as revealed by Maguire et al. (2013). In contrast to the children who showed N300 congruency effects only for objects, the adults in their study exhibited N300 differences between congruent and incongruent items for both objects and actions.

It is widely accepted that younger children have more difficulty managing verbs than nouns (Gentner, 1981). This may be related to the motor simulation issues observed in children under 11 years old — a difficulty that seems to disappear by 13 years of age. Experiential interaction with the environment may dictate the extent to which simulation is accomplished. Extended practice with multiple objects makes for a complex representation of action. Younger children are more limited in their experience and may thus exhibit a more constrained ability to simulate. Considering that the AIP plays a crucial role in the simulation of manual gestures evoked by language, it is thus conceivable that the degree of grip force reflects a complex interplay between the morphological and functional development of the parietal-frontal circuit, experience and skill level (see also Lu et al., 2009).

The majority of studies interested in the linguistic representation of action have made use of visually presented objects and short action sequence stimuli — in part, due to the underlying interest in specifying the nature of language deficits in dyslexic children. In general, these studies examined the performance between adults and children. The present study used auditorily presented material and investigated how children and adolescents differed in the expression of grip force to both nouns and verbs. Conceptually similar results to the cited studies were observed here also, suggesting that the linguistic mechanisms are consolidated by adolescence and that these mechanisms are independent of the type of afference.

Most of the studies investigating the relationship between action verbs and cerebral function have highlighted the novelty or the attentional preference of the parietal regions for language-related stimuli. The more specific contribution of the present effort was to underline that grip force is related, at least conceptually, to the morphological maturity of the fronto-parietal regions. There was no novelty effect in this study since the children did adequately explain or mimic all the target words, whether nouns or verbs. There was no new learning since all target stimuli were already known and adequately mimicked. There was no attention difficulty since all the participants showed adequate monitoring performance. Still, verbs elicited a significantly stronger grip force in adolescents only.

Two overlapping fronto-parietal circuits are actively involved in manual gestures. One is linked to the actual action; the other is involved in the simulation or motor imagery of that manual action. In addition, BA 44 (Broca's region) is activated when producing a manual gesture but is even more stimulated during simulation in adults (see Gerardin et al., 2000). This latter neural circuit is, in the adult, implicated in simulated hand action and would not be functional enough to elicit modulated grip force in children when listening to verbs.

Although this study extends the measure of grip force to younger populations of children and adolescents, the number of subjects in the sample requires caution in generalizing the results and conclusions to French hand action verbs only. This is currently being addressed in an ongoing study with bimanual measures of grip force in a large sample of children and adolescents.

Author statement

Victor Frak designed the study and contributed to all aspects and phases of the manuscript; David Labrecque tested the subjects and conducted the statistical analyses; Henri Cohen conducted the statistical analyses and contributed to writing the manuscript.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandc.2020.105673.

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