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"Embodied" language processing:

Mental motor imagery aptitude predicts word-definition skill

for high but not for low imageable words in adolescents

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ABSTRACT

Our study was designed to test a recent proposal by Cayol and Nazir (submitted), according to which language processing takes advantage of motor system "emulators". An emulator is a brain mechanism that learns the causal relationship between an action and its sensory consequences. Emulators predict the outcome of a motor command in terms of its sensory reafference and serve monitoring ongoing movements. For the purpose of motor planning/learning, emulators can "run offline", decoupled from sensory input and motor output. Such offline simulations are equivalent to mental imagery (Grush, 2004). If language processing can profit from the associative-memory network of emulators, mental-imagery-aptitude should predict language skills. However, this should hold only for language content that is imageable. We tested this assumption in typically developing adolescents using two motor-imagery paradigms. One that measured participant's error in estimating their motor ability, and another that measured the time to perform a mental simulation. When the time to perform a mental simulation is taken as measure, mental-imagery-aptitude does indeed selectively predict word-definition performance for high imageable words. These results provide an alternative position relative to the question of why language processes recruit modality-specific brain regions and support the often-hypothesized link between language and motor skills.

KEY WORDS: Embodied Cognition, Motor imagery, Language, Word imageability, Motor Action, Emulators

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1 - INTRODUCTION

Potential links between language and motor skills have long been discussed in the literature. Children diagnosed with SLI (specific language impairment), for instance, typically show deficits in fine and gross motor skills, both simple and complex (e.g., Hill, 2001; Sanjeevan et al., 2015). Similarly, children with Rolandic epilepsy have been diagnosed as showing language deficits in the absence of problems with other competences such as mathematics (Overvlient, et al. 2011). Interestingly, within the context of "embodied" language processing theories (Barsalou, Santos, Simmons, and Wilson (2008); Cayol and Nazir, submitted; Glenberg and Gallese, 2012; Pulvermüller, 2018), such a link is actually predicted.

According to theories of embodied language processing, brain structures traditionally considered to serve perceptual and motor processes are also recruited during the processing of language that refers to perception and action. A large number of empirical papers that provide evidence for such language-induced activity in modality-specific brain structures (henceforth abbreviated as LIAMBS) have been published over the past 15 years (e.g., Glenberg & Gallese, 2012; Fischer & Zwaan, 2008; Kiefer & Pulvermüller, 2012; Pulvermüller, 2018; Pulvermuller & Fadiga, 2010; Willems and Cassasanto, 2011; Willems & Haggort, 2007). Hauk et al. (2004) and Tettamanti et al. (2005), for instance, provided the first evidence that the processing of words and sentences denoting motor actions triggers activity in premotor and primary motor structures of the brain. As summarized in Binder and Desai (2011), similar observations have subsequently been made for other modalities. Hence, words denoting colors activate the fusiform gyrus just anterior to color-selective regions of extrastriate visual cortex; words denoting odors activate olfactory areas in the prepiriform cortex, etc.

Influential theories in the domain of embodied language processing i.e., the "Action-Perception Circuit" (APC) model by Pulvermüller (1999; 2013; 2018) or the "Language and Situated Simulation theory" (LASS) by Barsalou, et al. (2008), consider modality specific brain structures as integral part of the brain system that elaborates lexical semantics. Pulvermüller, for instance, propose that Hebbian learning

mechanisms bind brain circuits underlying the processing of word-form information with circuits related to the processing of visual object information (e.g., during the acquisition of a concrete noun), or action-related information (e.g., during the acquisition of action verbs). These integrated APCs are the neural basis of word semantics. Similarly, for the LASS-theory the re-enactment of experienced states in modality-specific systems underlies conceptual knowledge, and is an essential part of word semantics. With reference to Damasio's hierarchically organized convergence-divergence zones (CDVs; Damasio 1989; Meyer & Damasio, 2009), the LASS theory assumes that CDVs in cortical association areas assimilate information across modalities and drive the re-enactment process in the absence of bottom-up stimulation. However, the fact that lesions to modality specific structures do not systematically erase word knowledge (e.g., Arevalo et al. 2012; Bartolo, Cubelli, Della Sala, Drei, & Marchetti, 2001; Negri et al., 2007), and the observation that for one and the same word LIAMBS varies with linguistic context (e.g., LIAMBS is absent in negative and volitional sentences; Aravena et al., 2012; 2014; see also Zwaan, Taylor, and Boer, 2010), are not compatible with these accounts. Moreover, since processing an action word does not (automatically) provoke the execution of the depicted action, the structures in motor brain regions that are recruited by language processes need to be further specified.

Departing from the common view that modality specific brain regions underlie the elaboration of word *meaning* (e.g., Barsalou, et al., 2008; Glenberg and Gallese, 2012; Pulvermüller, 2018), Cayol and Nazir (submitted) therefore recently suggested that language processing recruits structures in modality-specific brain regions for *predictive* purposes. More precisely, the authors proposed that language processing takes advantage of "internal forward models" or "emulators" that evolved for motor control, in order to assess the *situation* depicted in the verbal stimulus. For a better understanding of this idea, we will briefly describe what emulators are, their potential neural bases, and how they could be exploited for language processing.

Emulators. An emulator is a hypothetical brain mechanism that learns the causal relationship between an action and its sensory consequences through experience (e.g., Wolpert et al. 1995; Wolpert and Ghahramani, 2000). In a very comprehensible

description of how emulators work, Grush (2004) referred to a robot by Mel (1988), which was designed to learn an optimal trajectory for reaching an object. The robot is made of an articulated arm, a visual system (a camera that "sees" the arm moving), and a connectionist network that allows the representation and linking of the two systems. This network comprises two bidirectionally interconnected neuron-like units, one that represents the visual information and one that represents the angles of the joints of the arm. By moving and observing the arm during the training period, the neuron-like units learns the relations between the action and the resulting state of the visual field. When the mapping is learned (which consists of knowing that if the visual state at time t_1 is v_1, a motor command m_1 will result in a visual state v_2 at time t_2), the robot can use this "internal forward model" to determine *offline* the optimal trajectory for attaining a visually specified goal before it executes the movement. In other terms, the robot can "simulate" or "imagine" a series of potential trajectories before choosing the optimal action. Since the interconnected neuron-like units serve as the basis for real as well as for the mentally simulated action/perception, the two tasks recruit partially overlapping representations in the two modality-specific structures.

In motor control, the predictions made by emulators are feed back into the motor loop to help assessing whether the unfolding action matches the desired outcome. Models of action control assume that these predictive processes are necessary because feedback from sensory receptors (in the muscle, skin, and joints, as well as from the visual system) that conveys information about body state is too slow to allow fast corrections of an ongoing movement (e.g., Grush, 2004; Pickering and Clark, 2014; Wolpert and Flanagan, 2001; Wolpert and Ghahramani, 2000; Wolpert et al., 1995). This covert computational stage thus accompanies any overt action (Jeannerod, 1995). The offline use of emulators (such as illustrated with Mel's robot) serves planning and learning, and is equivalent to "mental imagery" (Grush, 2004; see also Jeannerod, 1995; 2001).

Neural basis of emulators. A number of brain imaging studies indeed suggest that mental motor imagery and movement execution recruit partly overlapping brain regions, i.e. in the prefrontal cortex, premotor cortex, SMA (supplementary motor area), posterior parietal cortex, and primary motor cortex, as well as in the cerebellum and basal ganglia (see Jeannerod, 1995, 2001; Lotze et al., 1999; Grèzes & Decety,

2001; Munzert et al., 2009; Hétu et al., 2013; Hardwick et al., 2018; Lotze, 2013; Jiang et al., 2015; Ridderinkhof & Brass, 2015). A recent large-scale meta-analysis by Hartwick et al. (2018) that compared data from various neuroimaging experiments of motor imagery, action observation, and movement execution identified a premotor, parietal, and somatosensory network of brain areas that are recruited across the three tasks. Moreover, a study that used multivariate decoding techniques to investigate the functional organization of mental motor imagery and movement execution specified that the closest similarity in neural activation patterns in the two tasks is seen in the superior parietal lobule and the dorsal premotor cortex (Zabicki et al. 2017). Both of these latter brain regions, along with the cerebellum (Ito, 2008; Wolpert et al, 1998), have been associated with the elaboration of internal forward models, i.e., emulators (O'Shea & Moran, 2017; Zabicki et al. 2017).

Emulators and language processing. Studies that investigated the involvement of motor brain structures in language processing have revealed that processing an action word will recruit motor brain structures only when the action is relevant to the verbally depicted situation. Hence, while the action word "to sign" will trigger activity in motor structures of the brain when displayed in a sentence such as "Tom signs the contract," it will not do so in a sentence such as "Tom *does not* sign the contract" or "Tom *wants* to sign the contract" (e.g., Aravena et al., 2012; 2014; Zwaan, Taylor, and Boer, 2010). Note that in the situation described in the first sentence, Tom is performing an action while in the second and third sentences, we do not know what (action) Tom is doing. Since motor brain structures can remain silent despite the presence of words that refer to a motor action (and despite the fact that we still understand the sentence), such findings suggest that LIAMBS does not reflect processes related to the elaboration of word meaning per se. Rather, according to Cayol and Nazir, language processes recruit motor system emulators to profit from the associative-memory network related to these mechanisms, in order to model the verbally described situation (cf. "situation models," e.g., Zwaan & Radvanksy, 1998; Zwaan, Langston and Graesser, 1995; Zwaan, 2014). Note that modeling the situation depicted in a sentence such as "Tom signs the contract," for instance, offers far more information than given by the words (i.e., that it probably involves a pen, a sheet of paper, a table, etc.). Theories of language comprehension assume that such "situation models" are required to integrate

and make sense of verbally communicated content (Zwaan & Radvanksy, 1998; see also van Dijk & Kintsch, 1983; Johnson-Laird, 1983). This in turn makes it easier to verify, predict, and prepare for our interaction with the environment.

If the above hypothesis is correct and the linguistic system is indeed recruiting motor system emulators, language processing should depend on how well these emulators work. In nonpathological conditions, the latter should be a function of motor experience and of the learning history of each individual. Poorly adjusted motor emulators should result in 'clumsy' motor behavior (because of badly predicted sensory feedback due to missing motor experience) as well as in the reduced ability to perform mental motor imagery. Critically, if language processing takes advantage of these emulators, we should also see poor(er) performance for language processing. This should be particularly evident for highly "imageable" language content (in terms of sensory and motor aspects) because this is the information provided by emulators. The present study aims to test this hypothesis by establishing whether performance in a motor imagery task predicts performance in a word definition task.

1.1 - The present study

Our participants were neurotypically developing 11-13 years old adolescents. The decision to work with adolescents was based on the consideration that motor emulators in this population are not yet fully adjusted since adolescents have not yet reached their final body shape and size. Sub-optimal adjustments of emulators should make it easier to uncover potential parallels between motor and language skills because performance will not be at ceiling. Two different experimental paradigms were used to estimate participants motor imagery skills. These paradigms, which were taken from a study by Linkenauger, Lerner, Ramenzoni, and Proffitt (2012), and from a study by Frak, Paulignan, and Jeannerod (2001), will be briefly described in the following.

<u>The action capability estimation paradigm by Linkenauger et al. (2012).</u> The tasks proposed by Linkenauger et al. (see Figure 1) were originally used to predict social and communicative skills (operationalized via a questionnaire) in adolescents (age 9-13 years) with autism spectrum disorders (ASD). The tasks consist of asking participants to estimate whether they could perform simple actions without overtly

executing them and determining the size of the estimation error. Three tasks were tested (see Figure 1): i) a "Graspability" task in which participants had to indicate the maximal length of a PVC block at which they believed to still be able to lift the block by grasping it with the thumb and index finger[1]. ii) An "Aperture passability" task, in which participants had to indicate the minimal size of an adjustable hole in a board at which they believed they could still slide their hand through the hole such that the hand would just touched the sides of the board. iii) A "Reachability" task, in which participants had to indicate the distance of an object on a table straight in front of them, at which they believed it was just at the limit of their reach. The estimated ability (measured in cm) was then compared to the actual ability.

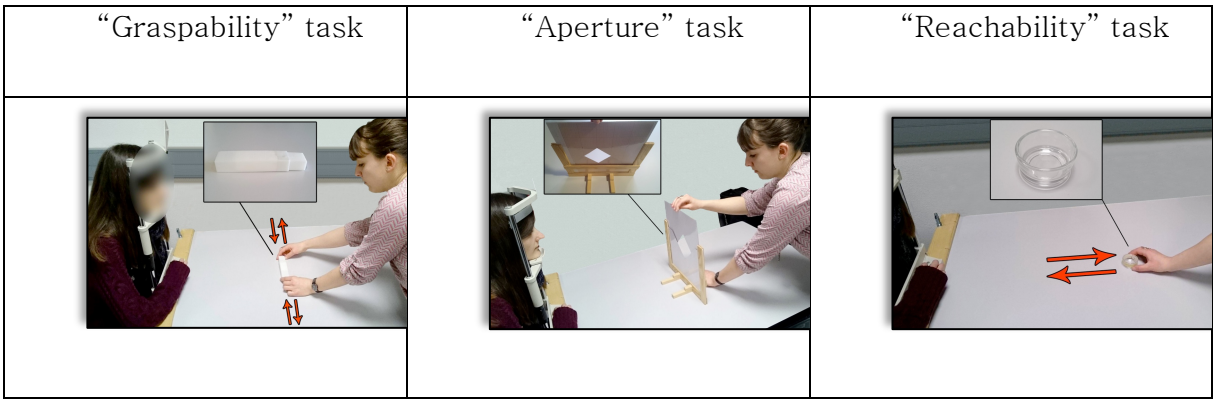

Figure 1. Illustration of the three different tasks used by Linkenauger et al. (2012). From left-to-right: the Graspability task, the Aperture passability task, and the Reachability task. For details see text.

Linkenauger et al. showed that adolescents with ASD had considerable difficulties in performing these estimations, and performance in these tasks predicted their social/communicative skills. By contrast, age-matched neurotypically controls performed the estimation tasks rather well, showing a moderate increased error in their estimations only in the Aperture task. While we considered the three estimation tasks as potentially suitable for our purpose, the rather high performance of Linkenauger et al.'s neurotypical control group, made us to add a further mental imagery task, i.e., the task by Frak et al. (2001). Frak et al.'s paradigm uses a more sensitive dependent measure, i.e. reaction times. However, in contrast to the Linkenauger et al.'s paradigm, this paradigm had not been tested with adolescents before.

[1] In the original version 18 square blocks of foam board of varying size were used as stimuli.

The paradigm by Frak et al. (2001). Frak et al.'s paradigm was designed to compare temporal parameters of overt and covert (mental imagery) motor behavior in a population of neurotypical adults. Participants were requested to judge (by pushing a button; see below) the difficulty of pouring a liquid from a little cylindrical container when grasped with the thumb and index finger at one of six predetermined positions (cf. opposition axis; see Figure 2). Unlike the estimation tasks of Linkenauger et al., this task measured response time and used a six-level independent variable.

In the original study, the overt condition consisted of asking participants to grasp (with the thumb and index finger) a container filled with water and to pour the water into a larger container (see Figure 2). The position of the fingers (cf. opposition axis) on the container was varied from −22° (difficult) to 56° (easy) to manipulate the degree of difficulty of the action. The data by Frak et al. showed that movement time systematically increases with the degree of difficulty. In the covered (action imagery) task, a computer monitor was used to schematically display the container, i.e., a disk, on which two small lines indicated the position where the index finger and thumb should be placed during the imagined action (Figure 2). The participants' task was to indicate, by pushing one of three prespecified computer keys, whether the task was easy, difficult, or impossible. Response time was the dependent measure. Frak et al. (2001; see also Fischer and Dahl, 2007) showed that the time to push the button in the motor imagery task reproduces in a quasi-identical way the temporal patterns obtained in the overt motor task. This result suggests that overt and covert actions recruit common brain mechanisms. In the present study, we used only the covert motor task.

The results from the two motor imagery paradigms (i.e. Linkenauger et al. and Frak et al.) were then used to predict performance in a language task, in which participants had to indicate whether a provided definition of a target word was correct or false. Target words were either high or low imageable words. If the proposal by Cayol and Nazir is correct, mental motor imagery scores should predict performance for high imageable words but not for low imageable words.

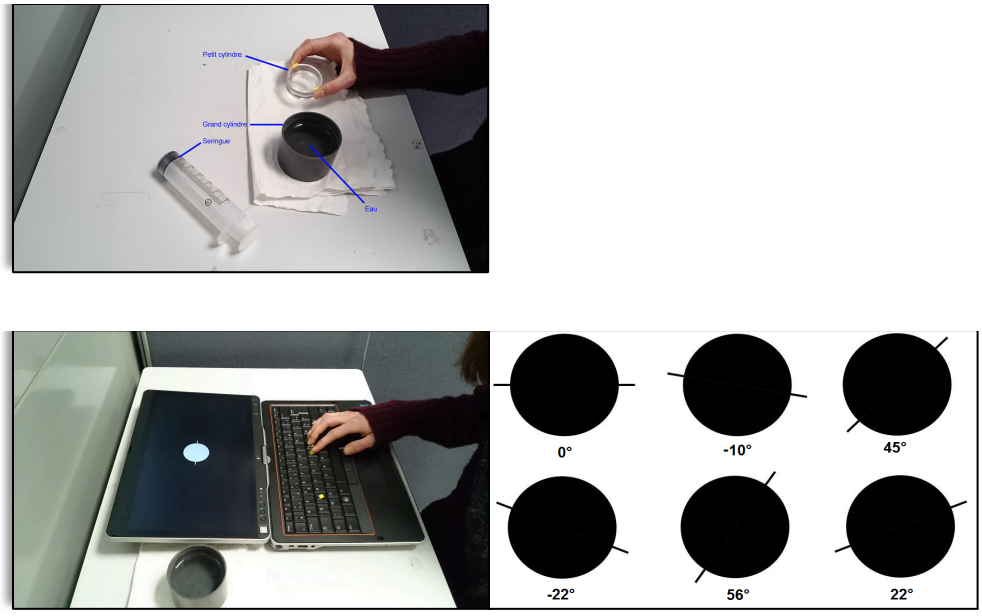

Figure 2. Illustration of the experimental paradigm used by Frak et al. (2001). Top panel, overt action in which participants are requested to grasp a cylindrical container filled with water with the thumb and index finger to pour the water into a container. Bottom panel, covert action. Left: Schematic display of the container, i.e., a disk, on a computer monitor. Two small lines on the disk indicate the position where the index finger and thumb should be placed during the imagined action. Right: Manipulation of the opposition axis from −22° to + 56°.

2 - METHOD

The Human Research Ethics Committee (CPP Sud-Est II) approved the study in compliance with French law. All methods were performed in accordance with relevant guidelines and regulations.

Testing took place at the laboratory and lasted about 1h30. There were breaks between the different tasks and participants were informed that at any point during the experiment they could interrupt the session for a break, or to simply end the experiment. Participants were also informed that the study was not intended to determine their level of performance (i.e. it was not an assessment of their skills). Parents gave their written informed consent and adolescents gave their assent to participate in the experiment. The order of the motor imagery paradigms and the word definition test were counterbalanced, with half of the participants starting with the language task. In the motor imagery sessions, half of the participants started with the

Frak et al. paradigm. Along with the computer software, the experimenter took note of the responses.

2.1 - Participants

From an initial pool of thirty-five adolescents, thirty participants (age ranged between 11 and 13 years; mean 12:9 years) took part in the experiment. None of these adolescents were diagnosed with dysphasia or intellectual disability, and they did not present any neurological or sensory processing disorder. They had no reported attentional problems or problems with mathematical logic. Two participants were left-handed. Participants and their parents gave their informed consent to the procedure prior to the experiment.

2.2 - Experimental design for the motor imagery tasks

2.2.1 - The paradigm by Linkenauger et al.

The three action capability estimation tasks were performed in one experimental block with short breaks between the tasks. Task order was counterbalanced using a Latin square design. Participants were seated at a white table devoid of visual landmarks. In contrast to the original study, we used a chinrest (see Figure 1) to stabilize participants head in order to guarantee that the distance to the table remained constant throughout the experiment. Participants dominant hand was placed on the table in front of the body, while the other hand remained under the table.

2.2.1.1 - Stimuli and apparatus

For the Graspability task, participants were presented with a white PVC block (3 cm x 3 cm x variable length) of adjustable length (smallest size 12 cm, largest size 23 cm). For the Aperture task, a diamond-shaped hole was created between two pieces of a (25.5cm x 33.5 cm) board; the bottom board was attached to a wooden stand (see Figure 1). The size of the hole was manipulated by moving the top piece of board upwards to increase hole size or downwards to decrease hole size. The size of the hole could vary between 0 cm to 16 cm. Paper rulers were fixed on the back of the board so that they framed the diamond shaped hole and indicated the size of the hole

as it was adjusted. For the Reachability task a small cylinder (diameter 4.5 cm; height 2.5 cm; weight 36 g) was used as the object to reach.

2.2.1.2 - Procedure

The Graspability task. Participants were presented with the adjustable PVC block. placed in front of them at a distance that would allow reaching it. The length of the block was manipulated in front of participants, by starting either with the smallest or the largest possible length. Participants were asked to indicate when the block reached the maximum length at which they thought they could still lift the block off the table. The experimenter then noted the indicated size in cm (values were rounded to 0.5 cm). The task was repeated 5 times in each of the two conditions (small-to-large and large-to-small), resulting in 10 trials per participants. Trial order was randomized. At the end of the experiment, the maximum length at which participants could actually lift the block was determined.

The Aperture Passability task. Participants were presented with the board placed at a distance that would allow sliding their hand through the hole in the board. Participants were presented with the largest or the smallest sized hole and the experimenter slowly decreased/increased the size of the hole until participants indicated that they felt they could fit the palm of their dominant hand (thumb parallel to the index finger) through the hole. The experimenter noted the participant's estimate (values were rounded to 0.5 cm). In one condition participants were instructed to proceed with the palm oriented vertically, and in the other condition with the palm oriented horizontally. Each of these two orientations were repeated 3 times in each of the two aperture conditions (small-to-large and large-to small) resulting in 12 trials per participants. Trial order was randomized. At the end of the experiment, the smallest aperture that participants could actually fit their hand through was assessed.

The Reachability task. The cylinder was place on the table straight in front of the participant (either near or far away). The cylinder was then moved either from the opposite side of the table (distance of 120 cm) towards the participants, or from a point

directly in front of the participants to the opposite side of the table[2]. Participants indicated when they thought the cylinder was at a location where they could just reach it with their dominant hand. After participants made their estimation, they were asked to close their eyes, and the experimenter measured the participant's estimate, i.e., the distance between the cylinder and a dot positioned directly in front of the participant (values were rounded to 0.5 cm). The task was repeated 5 times in each of the two directions (towards and away) resulting in 10 trials per participants. Trial order was randomized. At the end of the experiment participants reaching abilities were assessed.

2.2.2 – The paradigm by Frak et al.

2.2.2.1 – Procedure

The design followed the paradigm described in Figure 2. Participants were comfortably seated in front of a table with their dominant hand on the table. Prior to the experiment, participants were asked to perform the real motor task using a small and a large cylinder (Figure 2 upper panel). The small cylinder was filled with water. Participants had to grasp the small cylinder (5 cm in diameter and 2.5 cm high) using a precision grip formed by the thumb and index finger of their dominant hand and pour the water (without spilling it) into the large cylinder. They had then to return to their original hand position. The procedure was repeated four times.

In the experiment proper, a portable computer was placed in front of the participant with the monitor flat on the table surface (Figure 2 lower panel). The participant's dominant hand was placed on the keyboard, with the index, middle, and annular fingers on the 'j', 'k', and 'l' keys, respectively. Each trial consisted of the presentation of a central fixation point for 1 s, followed by the image of the disk, which stayed on the screen for 5 s. Each disk was marked with two contact points (two small lines) that defined six opposition axes at 0°, 22°, 44°, 56°, −10° (350), and −22° (338°) with respect to the frontal plane. The participant's task was to indicate as quickly as possible with a button press whether the previously experienced action of grasping

[2] In the original study the researchers used two more conditions in which the object was moved towards/away from the participants starting either at 30° or at −30° from center.

the cylinder with water and pouring the water into the container would be easy ('j'), difficult ('k'), or impossible ('l') with the fingers placed according to the opposition axis indicated on the disk. No actual movement was allowed. Ten measurements were taken for each of the six angles resulting in a total of 60 trials per participants. The delay between the onset of the stimulus and the button press was taken as an estimate for the duration of the mentally performed action.

2.3 - Experimental design for the language task

2.3.1 - Stimuli.

A total of 120 two-syllable common nouns, with a frequency of occurrence between 1 and 90 per million (freqfilm2; French database LEXIQUE 3.82 (http://www.lexique.org/), served as stimuli. Half of the words were low imageable words (< 3 on a 7-point scale; Desrochers and Thompson, 2009), and the other half were high imageable words (> 6.5 on a 7-point scale). Words were grouped into two lists, controlling for frequency and imageability, as shown in Table 1. There was no statistically significant difference between the two lists. The average frequency of high and low imageable words also did not differ.

	High imageability words		Low imageability words	
List 1	Imag. 6.82	Freq. 13.49	Imag. 2.71	Freq. 16.05
List 2	Imag. 6.78	Freq. 13.11	Imag. 2.76	Freq. 16.54

TABLE 1: Mean frequency and imageability for words used in lists 1 and 2.

A definition for each word was taken from the French encyclopedic dictionary "Larousse". When necessary, these definitions were edited to make them more accessible to adolescents. For each of the words, we also created an incorrect definition (see examples with approximate English translations in Table 2). For the experiment, the 60 correctly defined words of List 1 were combined with the 60 incorrectly defined words from List 2 to form 120 stimulus definitions of unique target words. The same was done for the 60 correctly defined words of List 2 and the 60 incorrectly defined words from List 1. Thus, we had two final lists of 120 items each. Half of the participants were tested with Final List 1, and the other was tested with

Final List 2. Thus, across all participants, we tested 240 words, once with the correct definitions and once with the incorrect definitions.

Low imag. correct	Le fait de porter assistance ou secours est un **soutien** *(Providing assistance or help is **support**)*
High imag. correct	Un instrument pour écrire avec de l'encre est **un stylo** *(An instrument for writing with ink is **a pen**)*
Low imag. incorrect	L'abandon d'un ami quand il a besoin d'aide constitue un **soutien** *(Abandoning a friend when he needs help is **support**)*
High imag. incorrect	Un instrument utilisé pour effacer quelque chose qu'on a écrit est **un stylo** *(An instrument used to erase something that has been written is **a pen**)*

TABLE 2: Examples of correct and incorrect definitions for high and low imageable words.

2.3.2 - Procedure.

The experimenter read the definitions and the target words orally to the participant. The participant's task was to decide whether the definition was correct by responding orally with "correct" or "incorrect". A break was introduced halfway through the experiment (i.e. after approximately 10 min).

3 – RESULTS AND DISCUSSION

3.1 - Motor imagery tasks

3.1.1 - The paradigm by Linkenauger et al.

For each participant, we determined their estimated ability, EA, (i.e. participants response) by averaging their performance over the different trials for each of the three tasks. These data, together with their actual ability, AA, (i.e. participants real ability) and the ratio of EA/AA are presented in Table 3. To compare our results with those of Linkenauger et al.'s neurotypical control group, we plot the EA/AA ratio of their control group next to ours (data in brackets). We then calculated the "Estimation-Error" for each participant as proposed by Linkenauger et al., by taking the absolute value of (1-EA/AA). This gives the proportion of errors relative to the actual ability, regardless of whether the response was over or under estimating the actual ability. The last row in

Table 3 plots the proportion of this Estimation-Error (with standard deviations) averaged over all participants. Note that this value cannot be deduced from the mean AA and mean EA in the table because the Estimation-Error is calculated for each individual participant prior to averaging the data. In the Linkenauger et al. study the corresponding data were presented as a graph, but they were approximately of the magnitude of .057, .138, and .033 for the Graspability, Aperture and Reachability tasks, respectively (total mean .076).

	"Graspability" task	"Aperture" task	"Reachability" task	Total
Mean AA	14.12 cm	9.28 cm	40.35 cm	21.25 cm
Mean EA	14.16 cm	9.85 cm	48.59 cm	24.20 cm
Ratio of mean EA/AA	1.00 (1.05)	1,06 (1.11)	1,20 (1.01)	1.14 (1.06)
Estimation-Error (SD)	.083 +/-.089	.085 +/-.084	.241 +/-.184	.14 +/-.07

TABLE 3: Mean estimated ability (EA in cm), mean actual ability (AA in cm), the mean EA/AA ratio, and the proportion of Estimation-Error (i.e. absolute value of (1-EA/AA) averaged over all participants for the three tasks. For a comparison, the mean EA/AA ratio of the control group in the Linkenauger et al. study is given in brackets. The last column gives the mean of the three tasks.

As evident from the table, on the average, participants overestimated their ability in all three tasks. However, with the exception of the Reachability task, the estimated and the actual ability are almost identical, indicating that our participants were very good in performing these two motor imagery tasks. When the proportion of Estimation-Error is considered (recall this is an error estimation irrespective of whether participants over- or underestimated their ability), the pattern remains nearly the same, with a relatively small proportion of errors in the Graspability and Aperture tasks. Note that Estimation-Errors of .083 and .085 in the Graspability and Aperture tasks correspond to 1.17 cm and .79 cm, respectively. The moderately elevated Estimation-Error found by Linkenauger et al. in the Aperture task (i.e. .138) was not replicated with our population. For the Reachability task, by contrast, our population showed a large Estimation-Error (.241; corresponding to 9,72 cm) that was not seen in the control group of the Linkenauger et al. study. The magnitude of the present Estimation-Error is actually comparable to that seen in Linkenauger et al.'s population of adolescents with ASD. We believe that the use of a chinrest in our study might have

contributed to this large Estimation-Error because the participants' arm was placed around the chinrest-support during the experiment (see Figure 1). This condition could have biased motor imagery because the Reachability task involved imaging moving the arm, which was restrained by the chinrest-support. We will come back to this point in the discussion section. The last column in the table gives the total mean over the three tasks. Following the procedure by Linkenauger et al. we used these values to predict participants' performance in the language task.

3.1.2 - The paradigm by Frak et al.

For each participant, the average response time was calculated for each of the 6 orientations independently of the type of response (i.e., 'easy', 'difficult', or 'impossible'). Values that exceeded 2.5 standard deviations from the mean were discarded from the analyses. Data were then averaged over the 30 participants. The left panel of Figure 3 plots this result as a function of the orientation of the opposition axis. As in the original study by Frak et al., a steady decrease in response time is seen as a function of the orientation of the opposition axis, from approximately 4200 ms at (-22°) to approximately 2800 ms at (56°). However, the response time of adolescents was much slower than the response time for adults who participated in the Frak et al. study, where the averaged maximal response time did not exceed 2100 ms.

The right panel of Figure 3 plots the individual data for four of our participants. As evident from this figure, response time varies substantially from one participant to the other. More critically, for some participants (e.g., participants p23 and p26), response time remained more or less stable across all orientations, indicating that these participants did not use mental imagery for responding.

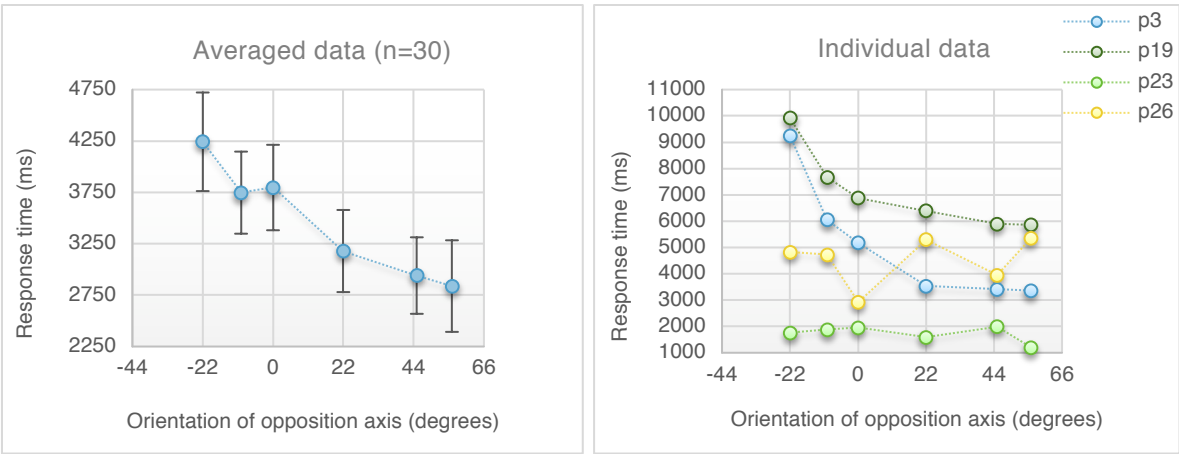

Figure 3. Left: Averaged response latency as a function of the orientation of the opposition axis of the fingers (−22°; −10°; 0°; 22°; 45°; 56°) plotted with the standard error of the mean. Right: Response latencies of four individual participants (p3, p19, p23, p26).

To characterize adolescent's aptitude for mental motor imagery, we calculated for each individual a normalized difference score between their highest and lowest response latency according to the following formula: (RTmax−RTmin)/(RTmax+RTmin). This allowed us to obtain a rough estimate of the impact of the orientation of the fingers' opposition axis relative to the child's overall response latency. Thus, a max−min difference of 500 ms for a child with fast response latencies results in a higher score than the same difference for a child with slower response latencies. We will refer to this score as the motor−imagery−aptitude score, or MIA score. For participants p3 and p19 in Figure 3, RTmax is at orientation (−22°) and RTmin is at orientation (56°). Their MIA scores are relatively high, with higher scores for p3. However, RTmax was not always at orientation (−22°). For p23, for instance, RTmax was at orientation (−0°), and for p26, RTmax was at orientation (56°). For this latter class of participants, max−min variations were typically smaller and/or overall response latencies were higher than for the first class of participants. Both elements indicate that participants had problems in performing the motor imagery task. MIA scores for this class of participants were lower than MIA scores for the first class of participants. We took the MIA score of our participants as an indicator of their mental motor imagery skill (with higher scores for better imagers). This score was used to predict participants' performance in the language task.

3.2 - Language task

From participants' 2x2 response types (i.e., response 'correct' for correct definitions; response 'correct' for incorrect definitions; response 'incorrect' for correct definitions; response 'incorrect' for correct definitions), we calculated nonparametric sensitivity A' scores (c.f. signal detection theory; Pollack and Norman; 1964; see also Stanislaw and Todorov, 1999) for both high and low imageability words. A' typically ranges from .5, which indicates that signals cannot be distinguished from noise, to 1, which corresponds to perfect performance. The results, averaged over the 30 participants, are given in Figure 4.

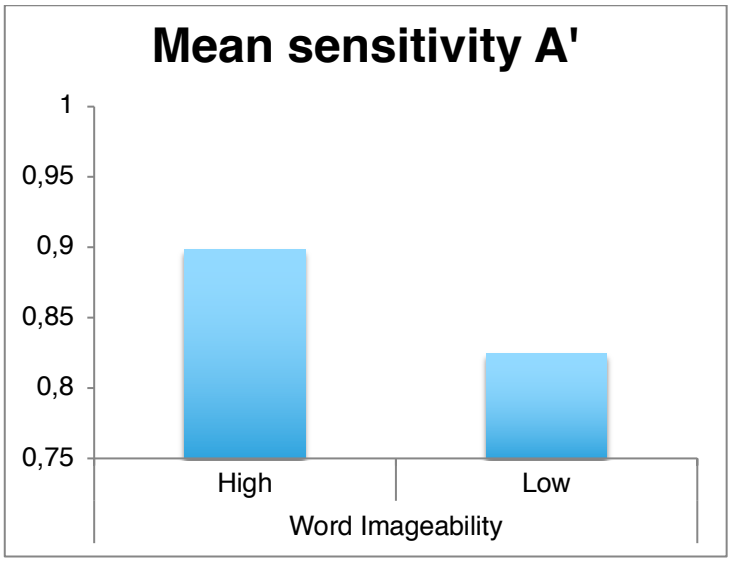

Figure 4: Mean sensitivity (A' scores) for high (left) and low (right) imageable words from the word-definition task.

A one-way ANOVA with the 2 imageability levels as within-subject variables showed a significant effect of imageability, with higher scores for high than for low imageable target words ($F(1, 29) = 10.602$, $p < .003$).

3.3 - Predicting A' scores in the language task from the motor imagery data

A simple linear regression was used to establish whether participants' performance obtained in the two motor imagery paradigms (i.e. Proportion of Estimation-Error and MIA scores) predict their A' scores in the language tasks for high and low imageable words.

3.3.1 – Proportion of Estimation-Error (Linkenauger et al.'s paradigm)

Prior visual inspection of the scatterplot of the proportion of Estimation-Error against A' scores indicated a linear relationship between the two variables. There was also homoscedasticity and normality of residuals. Figure 5 (top row) shows that Estimation-Errors did not account for the variability in the A' scores, neither for high nor for low imageable target words (high imageable words R^2= .051; adjusted R^2 = .017; F(1,28)=1.503, (n.s); low imageable words R^2= .00; adjusted R^2 = -.035; F(1,28)=009, (n.s). For additional information, the orange symbols present total Estimation-Error calculated without the results from the Reachability task, which did not account for the variability in the A' scores either.

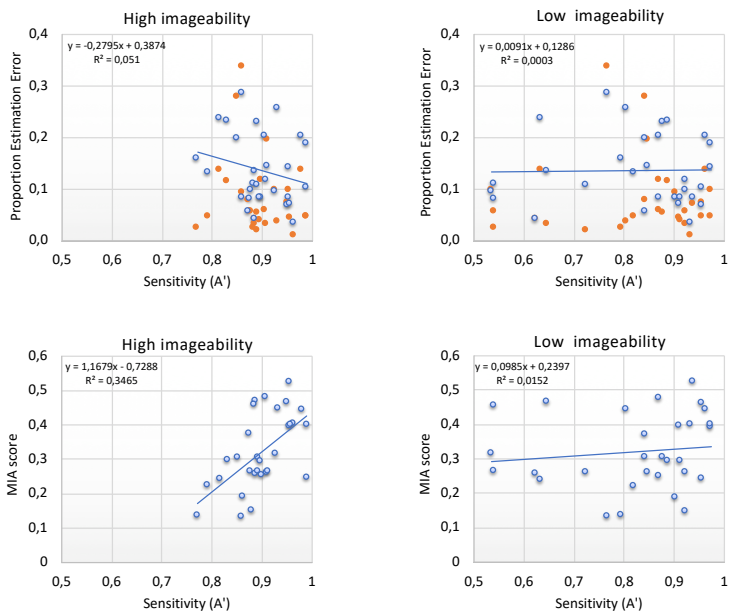

Figure 5: Sensitivity A' scores for high (left column) and low (right column) imageable target words plotted against the total Estimation-Error (top row) and the MIA scores (bottom row) for the 30 participants. The orange symbols in the top row presents total Estimation-Error calculated without the results from the Reachability task.

3.3.2 – MIA scores (Frak et al.'s paradigm)

Prior visual inspection of the scatterplot of MIA scores against A' scores indicated a linear relationship between the two variables. There was also homoscedasticity and normality of residuals. Figure 5 (bottom row) shows that for high imageable target

words, MIA scores accounted for 34,7% (adjusted R2 = .323) of the variability in the A' scores (F(1,28)=14.85 p=.001). By contrast, MIA scores did not predict A' scores for low imageable words (R^2 = .015; adjusted R^2 = -.02 F(1,28)=.431 n.s.).

3.4 – Discussion of the results

The motor imagery data obtained with the paradigm proposed by Linkenauger et al. did not allow predicting performance in the language task. As mentioned earlier, with the exception of the Reachability task, the Estimation-Error in our population is small. This could mask potential variations in the imagery skills of our participants. The large Estimation-Error in the Reachability task (which differs from the findings by Linkenauger et al.), by contrast, is very likely due to the way participant's arm was placed around the chinrest-support. This position would make an overt arm movement (i.e. reaching an object in front of the body) difficult. Vargas, Olivier, Craighero, et al. (2004) demonstrated that such constraint bias imagery performance. Using an imagery task of finger movements (i.e. joining the tips of the thumb and the little finger) these researchers showed that maintaining a hand posture that is incompatible with the movement to be imagined (i.e. index and thumb extended, the remaining fingers flexed, as opposed to index, thumb, and little finger extended) reduces the correlation between motor imagery duration and the duration of the actual movement. The Estimation-Error from the Reaching task should therefore not be taken to predict performance in our language task. However, without this task, the total Estimation-Error is probably too small to be meaningful. For illustration, the orange symbols in Figure 5 plots the total Estimation-Error when the results from the Reachability task is not considered. As evident from the figure for many participants the proportion of Estimation-Error is well below 0.1. In other terms, the Linkenauger et al. paradigm is probably not sensitive enough for testing imagery skills of neurotypical adolescents.

The results obtained with the Frak et al. paradigm, by contrast, confirmed our hypothesis. First, note that using this paradigm we replicated the results obtained by Frak et al., with a group of adolescents. This validates Frak et al.'s findings and shows that the paradigm is robust and can be used with neurotypical adolescents. More critically, data obtained with this paradigm predicts performance in the word definition test for high imageable target words only. This is what is expected if the processing

of (imageable) verbal content profits from the associative memory of motor emulators. Nearly 35% of the variability in the language task (for high imageable words) can be accounted for by participants motor imagery aptitude. However, on the background of the failure to obtain comparable results with the Linkenauger et al. paradigm, our results should be taken with caution. Although we pointed out factors that might explain the failure to predict performance in the language task from data obtained with the Linkenauger et al. paradigm, any strong conclusion about the link between motor skills and language should await further replications. Our motor-imagery-aptitude measure (c.f. MIA score) that we calculated for the results obtained with the Frak et al. paradigm needs also additional validation. The absence of variations in response time with the orientation of the opposition axis (e.g., a MIA score of 0) can certainly be taken as an indicator that response strategies other than motor imagery were used by the participant. However, whether smaller but systematic variations of response time with the orientation of the opposition axis are more indicative of a reduced aptitude for motor imagery than larger variations (see, for instance, participants p.3 and p19 in Figure 2) has to be established. How an overall longer response time should be interpreted and how this factor relates to motor imagery aptitude is also still an open issue. In summary, while the present results are promising with respect to the potential link between motor and language skills, they should be considered exploratory.

4 – GENERAL DISCUSSION

The literature on developmental motor and language disorders has repeatedly pointed to potential parallels between the two deficits (e.g., Hill, 2001; Sanjeevan et al., 2015). In the present study, we placed this hypothesized correlation within the context of embodied cognition. While classic models of embodied language processing (e.g., Barsalou et al., 2008; Glenberg & Gallese, 2012; Pulvermüller, 2018) consider that modality-specific brain structures contribute to the elaboration of word meaning, a recent proposal by Cayol and Nazir (submitted) directly implicates motor system emulators in the processing of words that are imageable in terms of sensory and motor aspects. According to Cayol and Nazir, modality-specific brain regions are recruited during language processing to better depict a verbally described situation (cf. situation model; Zwaan & Radvanksy, 1998; see also van Dijk & Kintsch, 1983; Johnson-Laird,

1983). For this, language processes take advantage of the associative-memory networks of motor system emulators. Given that these associative-memory networks evolve through bodily interaction with the environment and link motor action to their sensory consequences, they mainly concern motor and sensory information. In other words, information that we consider as "imageable". The present study was designed to test this assumption by determining whether motor imagery skills can selectively predict performance in a language task that involves high imageable words as opposed to low imageable words. One of two motor imagery paradigms that we tested, i.e., a paradigm that use reaction time instead of estimation error as dependent measure, produced the predicted results. Motor imagery skills, as measured with a paradigm first proposed by Frak et al. (2001), account for nearly 35% of variations in word-definition performance for high imageable words but not for low imageable words.

If these findings can be further confirmed, our results could open new perspectives on embodied language processing. First, our findings provide an alternative position relative to the question of why language processes recruit modality-specific brain regions. The fact that mental motor imagery aptitude predicts performance for high but not for low imageable verbal content is coherent with Cayol and Nazir's proposal that the linguistic system accesses modality-specific brain regions to profit from the associative-memory network of emulators. Exploiting this memory network, which contains content about bodily interaction with the environment, allows us to better "model" the verbally depicted situation (c.f. "situation models"; Zwaan & Radvanksy, 1998; see also van Dijk & Kintsch, 1983; Johnson-Laird, 1983). Thus, our interpretation contrasts that of the common view according to which LIAMBS serve the elaboration of word meaning via simulations of what words refer to (e.g., Barsalou, 2008; Glenberg and Gallese, 2012; Pulvermüller, 2018). The fact that motor imagery aptitude did not predict performance for low imageable words further suggests that the linguistic system has options other than mental imagery for modeling verbally depicted situations. Thus, the recruitment of motor system emulators is only one possibility among others to elaborate situation models (Cayol and Nazir, submitted). This latter assumption is also supported by the fact that individuals with 'aphantasia', who cannot voluntarily use mental imagery (Zeman et al., 2015), do not seem to have language problems. If aphantasia results from poor emulators or from the absence of

wiring between the linguistic system and modality-specific brain regions, this population must use strategies other than mental imagery for modeling verbally depicted situations. Investigations into how they process imageable language content might allow new insights into how the linguistic system works.

The present findings would also allow another perspective on the relation between developmental deficits in language and motor skills (e.g., Hill, 2001; Sanjeevan et al., 2015, Overvlient, et al. 2011). Iverson (2010) proposed that the acquisition of motor competences in general, allows infants to practice skills relevant to language acquisition. If motor development is delayed, the acquisition of skills relevant to language acquisition will thus also be delayed. According to Iverson the rhythmic hand and arm movements that precede the onset of reduplicated babble in infants, for instance, allow them to practice the rhythmically organized actions that are required for babbling. The transition from crawling to walking allows a broadening of the range of communicative referents and gives the infant a more active role in establishing interactions with caregivers and others (Iverson, 2010). Our data add to this list by suggesting that motor skills affect language performance because motor experience allows the development of associative-memory networks (emulators) that could be useful for imaging language content. Note that emulators constantly adapt as a function of motor exercise and practice (e.g., Flanagan and Johansson, 2002; Flanagan et al., 2003). If language processing profits from motor system emulators, the optimization of the function of emulators, i.e., through physical activity could have a positive impact on language. In line with this notion, several studies have pointed to a relation between physical activity, motor skills, and cognitive functions - including language - in normally developing children (for a recent comprehensive review, see Zeng et al, 2017). Hence, in addition to their contribution to the clinical domain, our data also provide arguments for parents to encourage their children to engage in more physical activities.

5 - DECLARATION OF COMPETING INTEREST

The author(s) declares no competing interests.

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