Seeing action simulation as it unfolds: The implicit effects of action scenes on muscle contraction evidenced through the use of a grip-force sensor

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ABSTRACT

Action simulation is a cognitive process that mentally simulates a motor act without performing it in the true external world. Simulation mechanisms play a key role in perceiving, feeling and understanding actions executed by others. However, very little is known about the process dynamics because of the absence of a behavioral tool to probe directly the action simulation process as it unfolds.

Twenty-seven healthy adults were required to hold a force sensor in a relaxed pinch-grip while viewing action videos of different intensities: wait (null); touch (low); move (medium); crush (high). When contrasting the variations in grip force (GFv) across conditions, results indicated that GFv started to increase and peaked respectively 200 and 400 ms after the moment of effector-object contact. In the wait condition, GFv remained flat throughout the trial confirming an absence of simulation engagement. Peak GFv was greater for the high and medium than for the low intensity videos suggesting greater brain activity overflow to the peripheral motor system when simulating more effortful body movements. These effects were negatively correlated with the motor imagery abilities of the participants, with greater GFv in the poor imagers as determined by the Movement Imagery Questionnaire.

Our results confirm the possibility of using a non-invasive grip force sensor to detect not only when individuals are cognitively engaged in action simulation but also to reveal the dynamics of the process. With various sets of videos, this paradigm offers new perspectives in the study of action simulation and its role in human cognition.

1. Introduction

Once a peripheral executor of central commands, the motor system is being regarded as a proper part of cognition (Rosenbaum, 2005). A rational for this idea is that predictions, which the motor system normally uses for goal-directed motor control, could be re-used in other domains, participating in perceptual, cognitive and social functioning more generally (Jeannerod, 2006; Grafton, 2009). The effectiveness of action simulation in fields requiring motor expertise is now widely accepted (*mentalising*: Lotze et al., 2003; *mental training*: Jackson et al., 2001) and recent studies have even suggested that action simulation could play a role in healthy-eating (Morewedge et al., 2010). As such, action simulation research has become a field widely used to orient protocols geared at enhancing motor learning and improving neurological rehabilitation in pathological populations. Hence, it is ever important today to develop adequate tools to probe directly the action simulation process as it unfolds. In the following, we report the use of a grip force paradigm to reveal not only the presence or absence of action

simulation but also the real-time unfolding of motor simulation mechanisms during the engaging cognitive activity of watching a video.

Simulation theories propose that the brain structures normally used for executing goal-directed actions can be dedicated to simulate these actions internally, without executing them overtly (Jeannerod, 2001). Hence, action simulation processes would have the same content as overtly executed movements and use the same central brain mechanisms for processing, but an inhibitory mechanism would block their overt execution down-stream in the motor hierarchy. As a true copy of a movement plan, action simulation would result from the reactivations of motor representations that reach consciousness and provide the means to "feel" the imagined actions as if it were performed (Crammond, 1997). The simulation process would play an important social function, providing the process of mind-reading by replicating and simulating the mental activity of the other agent (Gallese and Goldman, 1998). Most importantly, a simulation process would play a key role in both individual and social contexts by providing the means to simulate different action possibilities and thus, participate in the

selection process for best-fit possibilities (Haruno et al., 2001; Wohlschläger et al., 2003). The existence of such a cognitive process has been confirmed across the years in the field of experimental psychology. For example, one of the earlier studies by Shepard and Metzler (1971) showed that the time required for mentally rotating an object for future manipulation, is comparable to the time needed for actually rotating the same object, implicating a common process to recruit sensorimotor representations for imagining and producing. Later studies confirmed that action simulation retains many of the temporal regularities, programming rules and biomechanical constraints than those observed during the true voluntary movement of the body through space and time (e.g., *mental rotation task*: Wexler et al., 1998; *effects of hand dominance*: Decety and Michel, 1989; *movement laws*: Decety and Jeannerod, 1995; Decety et al., 1996). Overall, action simulation is thought today as a key process, fundamental for movement selection and preparation, motor learning and optimization but also for the understanding of intention through movement observation (Lewkowicz et al., 2015).

Seminal work by Jeannerod and collaborators went one step further by providing evidence of a similar neural substrate underlying executed, observed and imagined actions (Decety, 1996; Jeannerod and Decety, 1995; Decety and Grèzes, 1999). Brain imaging studies indicated that these very different behavioral tasks were characterized by similar activation patterns of the supplementary area, the premotor and primary motor cortices, the basal ganglia as well as the cerebellar areas (Ryding et al., 1993; Grafton et al., 1996; Decety et al., 1994; Iacoboni et al., 1999). More specifically, pixels activated during motor imagery represented a large fraction of the whole population of pixels activated during motor performance (Lotze et al., 1999); primary motor cortex activation reported during action simulation amounted to about 30% of the level observed during execution (Roth et al., 1996; Porro et al., 1996). The activation patterns of the motor cortices during simulation are in direct correlation with the degree of motor expertise characterizing the individuals engaging in the action simulation process (Meister et al., 2004; Calvo-Merino et al., 2005), reinforcing the consensus today that large brain overlappings are present during imagination, observation and imitation because of the need across these tasks of a common action simulation process (see the meta-analysis proposed by Caspers et al., 2010). A remaining question nevertheless lies within the understanding of the individual differences that have been described in certain studies with some participants recruiting motor cortices more or less than others during action simulation (e.g., Gerardin et al., 2000).

The functional patterns of brain activation are characterized by a certain degree of specificity. In a linguistic study by Hauk et al. (2004), participants were instructed to read action words relating to movements of the mouth, arm and leg. The fMRI data revealed somatotopic activation patterns: a somewhat specific activation in the primary motor cortex was observed in the arm- and leg-related word conditions whereas arm- and face-related stimuli activated the premotor cortex. Similar findings have been reported by others in action observation tasks. For example, Buccino et al. (2001) reported an fMRI study in which the brain activations in the premotor and the parietal regions were activated as a function of the effector used in the illustrated picture. When the actor performed the movement with the hand, the foot or the mouth, different areas of frontal and parietal cortices were activated in a somatotopical way with co-activation of related motor cortices. As such, action simulation processes may trigger the release of a minimal quantity of brain activity to those muscles that will contribute specifically to the future movement (Wehner et al., 1984; Prabhu et al., 2007). To confirm the role of these central activation patterns for movement facilitation, corticospinal excitability was measured using transcranial magnetic stimulation of motor cortex during both observed (Fadiga et al., 1995) and imagined arm movements (Fadiga et al., 1999). The findings in these studies indicated that motor evoked potentials (MEPs) are selectively increased in the finger flexor brain areas when a subject mentally activates finger flexion, whereas

the MEPs in the antagonist extensor muscle area remain unchanged. These findings and others (Aranyi et al., 1998) indicated a high-level of specificity of the central activation patterns for peripheral muscle preparation. However, other studies (Baldissera et al., 2002; Andersen et al., 1999) demonstrated a nonspecific facilitation of responses to transcranial magnetic stimulation. Recently, Komeilipoor and collaborators further reported that corticospinal excitability of the hand muscle was increased even when preparing for movement of other body parts, e.g., teeth clenching and ipsilateral foot dorsiflexion (Komeilipoor et al., 2017). Due to neural coupling principles, motor simulation could lead to the modulation of the resting muscle-tone not only of the prime-mover muscle for the mentally simulated movement, but also of other muscles that contribute to body stability for goal-achievement. In the present study, foot- and hand-videos were used to extend our current understanding of the neural interactions underlying simultaneous contraction of muscles in different body parts during an action simulation task.

Activation specificity has also been suggested as a function of the adopted perspective taken during the simulation process (Guillot et al., 2009). On the one hand, when simulating from a 3rd person perspective, visual information is engaged predominantly (Jackson et al., 2006). One imagines someone else performing the action, setting oneself outside of the scene (Wexler et al., 1998) to simply observe a 3rd party's body in movement. On the other hand, simulation from a 1st person perspective can offer a rich visual scene (Jiang et al., 2015) but it is kinesthetic in essence as one can truly imagine the multi-modal sensations that would be experienced during own body motion (Hétu et al., 2011). In a recent brain imaging study, Keysers and Gazzola (2014) had participants watch a person being touched and reported an activation of the secondary somatosensory cortex, which confirmed the key role of sensations during 1st person perspective taking. Keysers and colleagues discussed that visual and especially kinesthetic motor simulations are triggered when imagining oneself moving, through the activation of the sensory tactile and proprioceptive representations of own body movement. Hence, in contrast to 3rd person perspective, action simulations from a 1st person perspective may "feel more real" and be associated to greater overflowing of brain activity to those muscles that participate in a simulated action. Such possibility has not – to our knowledge – been tested directly. Indeed, questionnaires with well-defined instructions have been created and validated to get individuals to engage in one or other types of action simulation processes (Loison et al., 2013). The specificity of the questions provides the means to gain an estimation of the ability of an individual to engage in an action simulation process either from a 3rd person perspective (Visual Motor Imagery - VMI) or from a 1st person perspective (Kinesthetic Motor Imagery - KMI), by scoring the vividness level of the experience. Nevertheless, questionnaires do not provide objective measures about the behavioral consequences of the action simulation process on the motor system.

The difficulty associated with the exploration of action simulation processes is indeed the fact that there is limited access to a direct monitoring of the type of activity a participant is truly engaged in. Compatible studies have emerged as a powerful paradigm to reveal objectively the presence/absence of action simulation. Indeed, when participants are instructed to execute a finger movement identical to that observed on a screen, their responses are initiated faster in the compatible than in the incompatible trials in which the executed movement is different from the movement seen (Brass et al., 2001; Tucker and Ellis, 2004). It is thought that while observing the action video, participants engage in a simulation process in order to understand the motor intention; during this simulation, the cortical activity overflows to the motor system, increasing slightly the muscle resting baseline activity level, which in turn facilitates the true activation of that muscle group, when the movement is truly to be performed. Nevertheless, this approach does not cue the time-course of the simulation process. In an attempt to study the dynamics of action simulation,

Gangitano et al. (2001) had participants watch videos in which a reaching-grasping action was executed and the MEPs were recorded. The amplitude of MEPs varied according to the time and the progress of the observed action: MEPs were larger when observing an increase in hand aperture, and were smaller during the closing of the grip. These results were also reported in the study by Alaerts et al. (2012) who, in addition, showed that the MEPs correlated to the excitability of the cortico-spinal system that was modulated according to the weight of the object manipulated in the video. These studies are very informative as they reveal that action simulation possesses a certain dynamic pattern. The objective here was to further study simulation dynamics with a non-invasive technique that could be widely and easily deployed both in healthy and clinical populations.

The grip force paradigm is a non-invasive technique that was developed in the field of language research (Frak et al., 2010; Aravena et al., 2012; Nazir et al., 2017) to measure not only the presence or absence of action simulation but especially the time course of brain activity overflow to the peripheral motor system. As when listening to action coded verbal sentences, we built a complete set of no-action and action videos to confirm the specificity of action simulation as a function of action intensity, effector and intention to act. To do so, an actor was instructed to perform object-directed actions of different intensities. We coded for trials in which a person waited, touched, moved or crushed objects of different sizes. The actions were performed with the foot or with the hand to assess effector specificity but also to see whether our paradigm could reveal those cases for which individuals would not want to engage in the simulation process (e.g., crush a hard object with the hand). The videos lasted approximately 5 s and were staged in a totally neutral environment.

Action simulation modifies the motor system as a function of the quantity of brain activity that overflows to pre-activate the muscles for future movements (Jeannerod, 2006). Based on the action simulation literature, we predicted that detectable brain activity overflow to the peripheral motor system would modulate the grip-force recordings when individuals engage in active simulation, with greater peaks of grip force variations when watching high versus low intensity action videos. With the ability to record the change in muscle tone in real-time, we aimed to demonstrate that action simulation is a dynamic process, time-anchored to action goals. Hand and foot-action videos were included to test the degree of specificity of the central activation patterns for peripheral muscle preparation, with the idea that grip-force modulations would be observed not only when observing hand-movements, but also when watching videos using nonhomologous limbs because of the existence of neural coupling to provide body stabilization during goal-directed actions. Finally, we collected complementary information about the participants in order to assess the nature of possible individual differences. Studies have reported that normal aging induces a cortical disinhibition (Papegaaij et al., 2014) which is associated to an increase in corticospinal excitability (Baudry and Duchateau, 2014; Baudry et al., 2015) and a decline in postural control. More specifically related to the present study, elderly participants were reported to have greater corticospinal excitability than young adults in a task for which they observed, imagined or performed a balance task (Mouthon et al., 2016). In line with these results, we postulated here that young participants with weaker capacities in cognitive inhibition should be characterized by greater corticospinal excitability revealed as an overall increase in grip force variations.

2. Material and methods

2.1. Ethics statement

All of the participants in this study gave an informed written consent. In accordance with the Helsinki Declaration, the study was approved by the Ethical Committee of the University of Lille – Human Sciences (Comité d'éthique d'établissement en sciences du comportement – 2015-8-S35).

2.2. Participants

The sample was constituted of 27 French undergraduate students with normal-to-corrected vision (15 females; 18–44 years old; mean age = 23.77, SD = 4.86). They reported an absence of both motor deficits and family history of psychiatric or neurological disorders. All participants were revealed to be right-handed as defined with the Edinburgh Inventory test (Büsch et al., 2010).

2.3. Apparatus and stimuli

2.3.1. Equipment and data acquisition

Participants were seated in front of a table on which was placed a screen (ELO screen, ET1915L, 19 in., 60 Hz refresh rate) that was used to display the visual stimuli (videos of action scenes). A unique computer (HP Zbook 17, Intel i7-4800MQ, 2.70 GHz, 8 GB; Windows 7) was used for stimulus presentation and data recording through a 16 bit DAQ National Instrument data acquisition card. To ensure synchronization, a trigger line was acquired by the DAQ card together with the grip force measurements. The MATLAB software read the video-list in a pseudo-randomized order and set two triggers on the force-curve inputs to indicate the playing beginning and end of each video. The triggers were measured to have a time-delay of 5 ms, approximately. The incoming force signals were recorded from a standalone 6-axis load cell of 68 g (ATI Industrial Automation, USA; Mini40, calibration SI-40–2) that was held by the participants between thumb and two fingers (see Fig. 1). In the present study, as in Nazir et al. (2017), preliminary data confirmed that the force torques were negligible due to the absence of voluntary movement. Two of the three main forces that were recorded, i.e., the longitudinal force Fx and the radial force Fy, remained steady throughout the experiment trials. Hence, only the compression force Fz was reported here in milli-Newtons (mN).

2.3.2. Stimuli

Videos were created as stimuli to offer a selection of action scenes and no-action scenes. The videos depicted an actor (face not seen) using either the hand or the foot to perform an action directed towards an object. In these videos, the actions started from the right and unrolled towards the left. Four different action intensities were considered (see Fig. 2). The Low Intensity videos corresponded to those videos in which the actor delicately touched a fruit (cherry, apple, orange or strawberry) or an object (small or large wooden dowels). The Middle Intensity videos corresponded to those videos in which the actor grasped with the hand or kicked with the foot the fruits or the wooden objects (Fig. 1-left). The High Intensity videos corresponded to those videos in which the actor crushed either with the hand or with the foot the fruits or the objects. Finally, in the Wait action scenes, participants saw video clips of a hand or a foot immobile 33 cm away from a stationary fruit or object (Fig. 1-right). This Wait condition was added in order to control whether motor simulation would be afforded simply by the presence of an immobile effector, close to a graspable object.

All trials were presented twice providing a total of 96 video-clips ((4 fruits + 2 objects) * 4 intensities * 2 effectors * 2 repetitions). The videos lasted approximately 5 s and were presented in semi-randomized order by blocks of 3 min, which enabled the viewing of 16 video clips per block.

2.4. Procedure

After reading the information letter and signing the consent form, participants were required to fill out a questionnaire of fatigue before the beginning of the experimental session. The participants were then comfortably seated in front of a screen at an eye-screen distance of 60 cm. The grip-force sensor was placed near their right hand. All
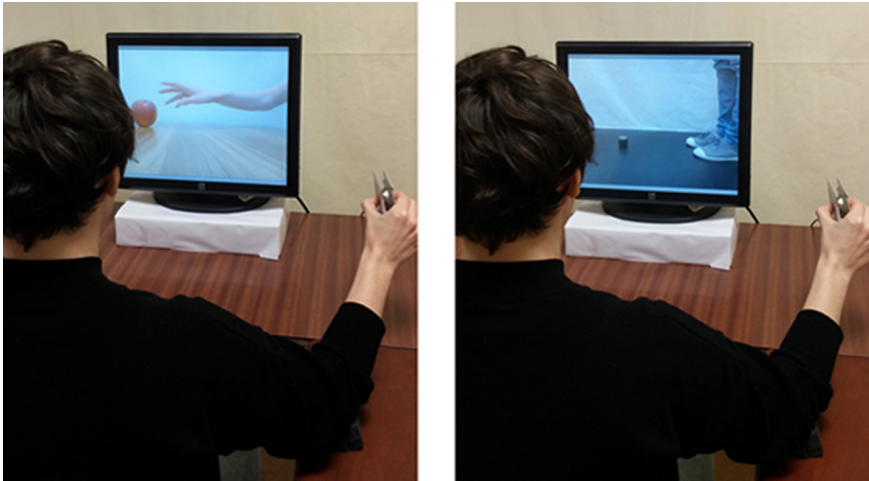
Fig. 1. Two exemplar pictures of the experimental setup are presented with a typical participant holding the grip force sensor between thumb and two fingers. Participants were instructed to hold the object with a constant 1.5 Newton of force while watching action videos (left panel) and no-action videos (right panel).

individuals participated in a unique experimental session lasting 75 min approximately that was subdivided in 4 parts.

In the first part of the session, the participants were asked to rest their right arm on the table and hold the load cell between the thumb, index and middle finger of their right hand, using a precision grip. The participants' task was to tilt the grip-force sensor slightly upwards to avoid resting the load cell on the table. When ready, participants were invited to hold the cell with a constant grip-force pressure of 1.5 Newton, which was adjusted before the experiment. While maintaining this relaxed and comfortable hand-posture, they were instructed to watch the different Action and No Action videos. In order to verify that participants were actively exploring the scenes, their explicit task was to observe the scene and count how many objects or fruits were contained within a block of trials. To avoid muscular fatigue, a break was imposed to the participants at the end of each block. At the end of the experimental session, the participants filled out the questionnaire of fatigue for a second time.

In the second part of the session, participants were required to fill out the Movement Imagery Questionnaire (Loison et al., 2013) that

evaluates the explicit ability to perform action simulations from a 1st and a 3rd person perspective. More specifically, participants were instructed to perform the action that was described in the questionnaire. Then, they were instructed to imagine doing the same action without moving (1) by creating a visual image of the action (visual motor imagery - VMI) or (2) by feeling their body move (kinesthetic motor imagery - KMI). The durations of the executed and imagined movements were recorded with a stopwatch, which was controlled by the experimenter when the participants indicated verbally the initiation ('GO') and the termination ('STOP') of the true or imagined actions. At the end of each series, the participants rated the quality of the mental image, i.e. the clarity and the easiness with which they were able to perform the VMI and KMI tasks, using a 7-point Likert scale. We will refer to this as the vividness indicator in the following sections. In addition, for each participant, the mean accuracy of motor imagery was calculated by computing the percentage of differences in time between the true and the imagined movement, following the formula: {(Mental duration – Execute duration) / Mental duration × 100}, for each of the KMI and the VMI items.
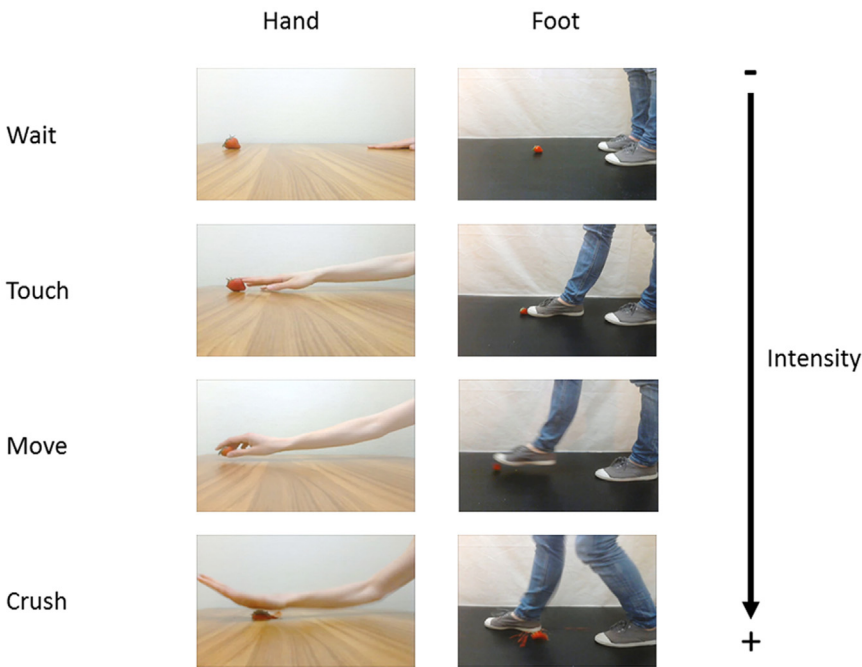

Fig. 2. Typical action videos were created with different effectors (Hand; Foot) and with body movements of different intensities for the trials in which the manipulated object was a strawberry. The different action intensities are defined as increasingly strong from no-action (Wait) to contrasting levels of action energy (Touch; Move; Crush).

In the third part of the session, participants were invited to watch 10 pre-selected videos to conduct a post-test evaluation using a 7-point Likert scale. The participants' task was here to (1) rate the intensity of the action videos and (2) the vividness of the KMI motor imagery induced by the observation of action videos from a 1st person perspective.

The fourth and final part of the session was dedicated to the use of the BIS/BAS questionnaire (Carver and White, 1994) to evaluate the inhibition abilities of each participant. This 24-item self-report questionnaire measures two motivational systems: the behavioral inhibition system (BIS) evaluates the motivation to avoid aversive outcomes while the behavioral activation system (BAS) codes for the motivation to approach appetitive outcomes. Only the BIS scores are reported here (score range 7–28, with higher scores indicating lower inhibition abilities). Participants were then invited to fill out the questionnaire of fatigue for a third and last time, before being debriefed about the overall purpose of the study.

2.5. Analysis

Prior to data analysis, each component of the force signal was low-pass filtered at 15 Hz with a fourth-order, zero-phase, low-pass Butterworth filter. The Fz signals were then segmented offline into 2000 ms epochs, spanning from -1000 ms prior to the effector-object contact time to 1000 ms after the effector-object contact time. An automatic artefact rejection was used to remove segments surpassing an amplitude range of $+/-$ 200 mN with respect to the baseline and/or showing an amplitude change of more than 100 mN, within a period of less than 100 ms, which is indicative of finger movements (Nazir et al., 2017). Overall, 26.8% of trials were revealed to contain such artefact in the present study (the proportion of rejected trials per condition is presented in Supplementary material 1). Female participants were characterized by a mean grip force level of 1.56 N whereas the males used a mean level of 1.59 N indicating that all participants were able to follow instruction and that there was an absence of gender effect.

In order to analyze the variations in grip force, each movie was divided in a set of images. With this technique, two temporal indexes were determined. The first temporal index t_0 was determined as the moment at which the Effector (the actor's hand or foot) touched the object. For the videos in which there were no actions (Wait condition), the t_0 was determined according to the mean t_0 of the other conditions. The second index was the moment of movement Initiation, t_I, which corresponded to the moment at which the effector began to move. For each condition, t_I corresponded to the mean t_I of all videos of that condition. Once the t_I was determined, grip force baseline GF_b was defined according to the interval $[t_I -200$ ms; $t_I]$. On all trials, a baseline correction was then performed by subtracting the GF_b from the GF level of that trial. Additional information is available on the temporal indexes used for each action intensity and effector type, in Supplementary material 2.

The GF levels were averaged across participant and trial type. Trials were realigned to t_0 and eight periods were determined. Mean trials for the two extreme conditions (Wait vs. Crush) are presented in Fig. 3 with an indication of the different time periods and corresponding picture-tags. The first period P1 corresponded to the interval $[t_I; t_I + 100$ ms]. The second period P2 was set as the 100 ms time window before object-effector contact $[t_0$-100 ms; $t_0]$. The three following periods were determined according to the timing constraints set by the processing of visual information (Fize et al., 2000). The P3 period $[t_0; t_0 + 100$ ms] is thought to correspond to the low-level processing (identification of shape, color and direction) while P4 $[t_0 + 100$ ms; $t_0 + 200$ ms] corresponds to the high-level processing (categorization of visual information). A period P5 spanning from $[t_0 + 200$ ms; $t_0 + 300$ ms] is thought to correspond to the motor simulation processing taking place to induce true motor action. Finally, three other periods were determined to tag the overflow dynamics of action simulation: the P6 $[t_0 + 300$ ms; $t_0 + 400$ ms], the P7 $[t_0 + 400$ ms; $t_0 + 500$ ms] and the P8 $[t_0$

periods $[t_0 + 500$ ms; $t_0 + 600$ ms] were determined as the periods in which the maximum grip force variation (GF_v) should be observed.

For each action Intensity (Wait; Touch; Move; Crush) and Effector (Hand; Foot), mean GF_v of the eight time windows (P1 - P8) were compared to those values measured during baseline. For the windows that presented significant GF_v with respect to baseline, comparisons were conducted between conditions using repeated-measures Analysis of Variances (ANOVA) and post hoc Tukey analyses were used when required. Finally, correlation scores were computed between the mean GF_v obtained in the P5 and the P6 time windows, and (1) the VMI and KMI scores obtained in the Movement Imagery Questionnaire and (2) the inhibition scores obtained in the BIS questionnaire.

3. Results

The score of fatigue did not vary throughout the experiment, indicating that the participants were not tired out by the experimental task ($F_{(2,60)} = 2.89$, $p = .07$, $\eta^2 = .09$). Participants judged the intensities of the action videos correctly with significantly different scale ratings as a function of action Intensity ($F_{(2118)} = 177.39$, $p < .001$, $\eta^2 = .75$). Post hoc analyses confirmed that participants gave the greatest ratings for the Crush Intensity videos ($X_{mean} = 5.77$, SE = .17), intermediate ratings for the Move Intensity videos ($X_{mean} = 3.94$, SE = .17) and the lowest ratings for the Touch Intensity videos ($X_{mean} = 1.79$, SE = .08, $p < .001$). It was easy for the participants to imagine themselves performing the actions using the seven-point Likert scale ($X_{mean} = 5.42$, SE = .21). Indeed, the ratings were significantly different from 0 for all levels of Intensities ($p < .001$). The simulation of the action seen was vivid ($X_{mean} = 4.56$, SE = .27) and significantly different from 0 for all levels of Intensities ($p < .001$). There was an absence of Effector main effect and of Effector interactions for all above mentioned analyses ($p > .100$).

GF_b was similar across conditions with an absence of main effects of both Intensity ($F_{(3,75)} = .988$, $p = .403$) and Effector ($F_{(1,25)} = .683$, $p = .416$). After subtracting for each individual trial the GF_b from the overall GF, results revealed that mean GF_v was significantly different from 0 in the Move and the Crush intensities (see Supplementary material 3). For all temporal periods, mean GF_v were not significantly different from 0 in the Wait and the Touch action intensities.

3.1. Effects of intensity across time

There was a main effect of Intensity on mean GF_v ($F_{(3,78)} = 10.353$, $p < .001$, $\eta^2 = .285$, see Fig. 4A). The Tukey post hoc test revealed significant differences between the Wait ($X_{mean} = -3.90$ mN, SE = 2.27) and the Move Intensities ($X_{mean} = 8.45$ mN, SE = 1.85, $p < .001$). Moreover, significant differences were revealed between the Wait and the Crush Intensities ($X_{mean} = 9.01$ mN, SE = 1.83, $p < .001$). There were no significant differences between the GF_v in the Wait and in the Touch Intensities ($X_{mean} = 2.65$ mN, SE = 2.19, $p = .073$), even if a clear tendency for grip force release was observed in the Wait trials only.

The following results are illustrated in Fig. 5. The main effect of Time was significant ($F_{(7,182)} = 13.262$, $p < .001$, $\eta^2 = .338$) with smaller mean GF_v in P1 ($X_{mean} = -.89$ mN, SE = .35) than in P2 ($X_{mean} = 1.14$ mN, SE = 1.26), P3 ($X_{mean} = 3.09$ mN, SE = 1.29), P4 ($X_{mean} = 4.19$ mN, SE = 1.35), P5 ($X_{mean} = 5.56$ mN, SE = 1.52), P6 ($X_{mean} = 6.28$ mN, SE = 1.65), P7 ($X_{mean} = 6.73$ mN, SE = 1.75) and P8 ($X_{mean} = 6.34$ mN, SE = 1.77). The Tukey post hoc test confirmed that P1 was similar to P2 ($p = .559$) but significantly different across all other Time periods (P3: $p = .005$, for all other periods: $p < .001$). Moreover, P2 was significantly different across all Time periods after P5 ($p < .001$). The post hoc test confirmed the differences between P3 and P7 ($p = .016$) and P8 ($p = .050$). However, there were no differences between P4 and the following time periods (P5: $p = .906$, P6: $p = .517$, P7: $p = .256$, P8: $p = .477$), P5 and the next periods (P6:
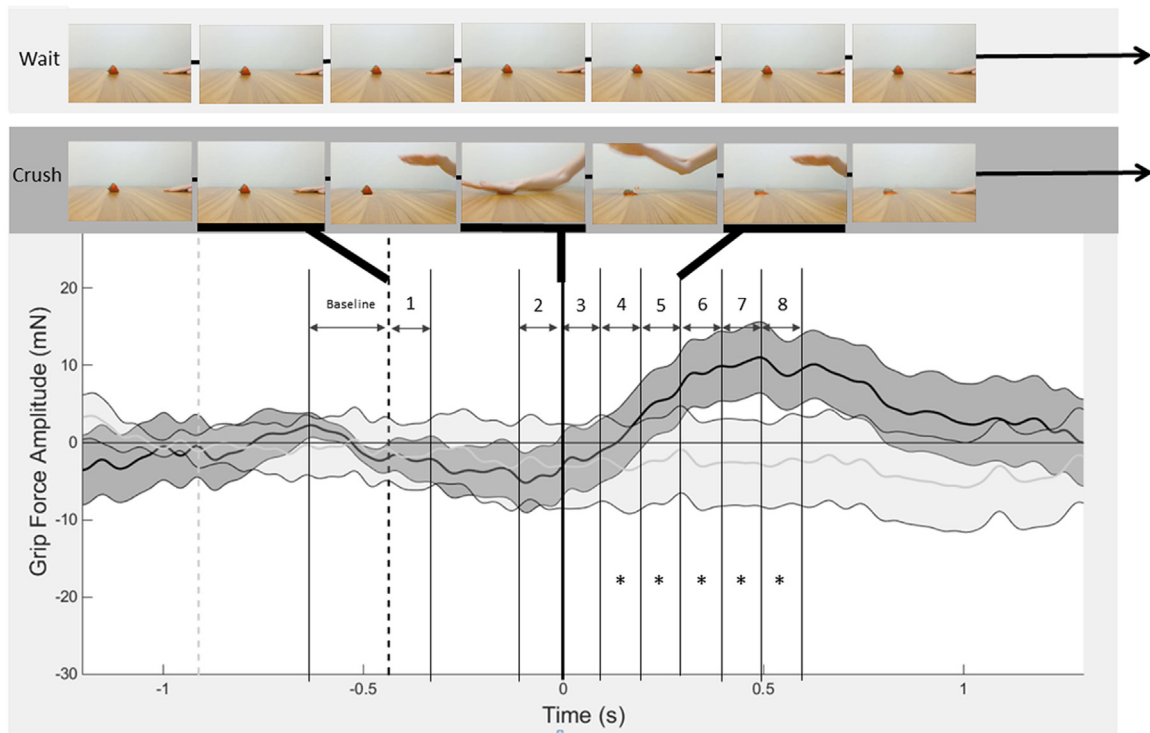
Fig. 3. Modulation of the grip-force levels are presented as a function of the time periods, after effector-movement onset for no-action videos (Wait – *light grey*) and for High Intensity action videos (Crush – *dark grey*). The curves illustrate the variations in grip force amplitudes between the baseline and the peak responses that occur within a time window of 320–800 ms after the effector touches the object. No significant effects were observed for grip-force amplitude variations in the no-action videos and in the low intensity action videos.

p = .998, P7: p = .959, P8: p = .996), between P6 and the next Time periods (P7: p = .999, P8: p = 1.000) – these results oriented our choice to use P5 and P6 for the correlation analyses.

A significant interaction between Time and Intensity was revealed ($F_{(21,546)}$ = 11.356, p < .001, η^2 = .304 – see Fig. 3) indicating an absence of differences between action Intensities in the first time periods (P1-P3) and significant differences between the No-Action and Low Intensity action videos, on the one hand, and the Middle and High Intensities action videos in the later Time periods (P4-P8), on the other hand.
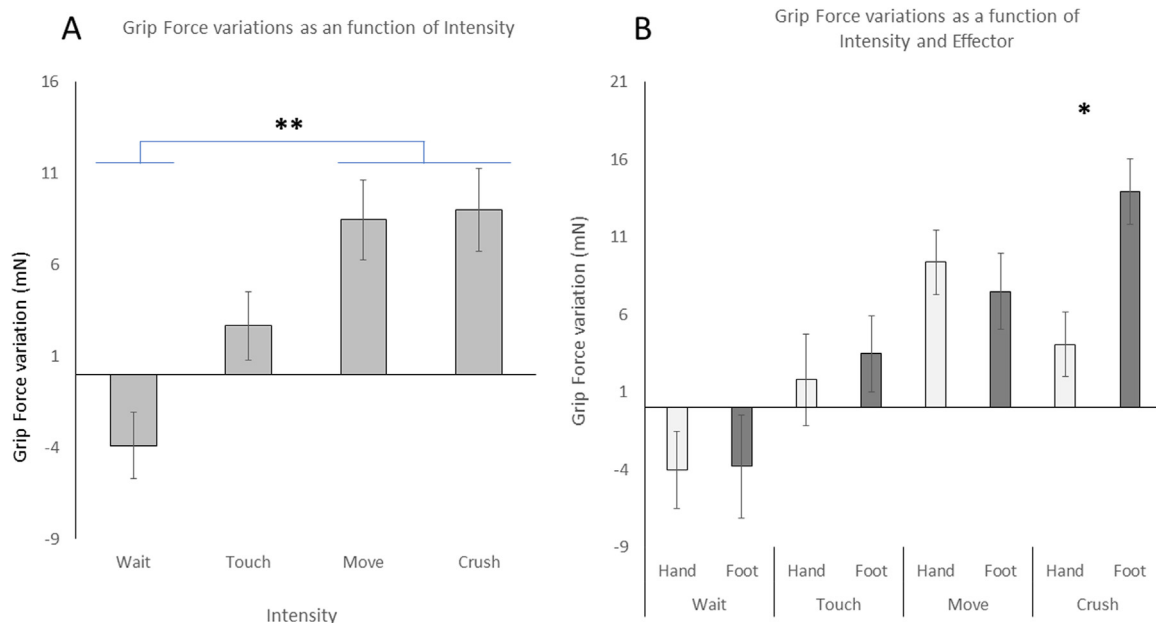

Fig. 4. Mean GF variations across all periods of time (from P1 to P8) are presented as a function of the intensity of the action videos (Touch, Move, and Crush) in contrast to that observed in the no-action videos (Wait). **Panel A.** Results are presented across all trials as a function of video type. **Panel B.** Results are presented as a function of video type and effector (Hand: *light grey*; Foot: *dark grey*) to present the significant Intensity * Effector interaction that was observed in the Crush High intensity action videos only.
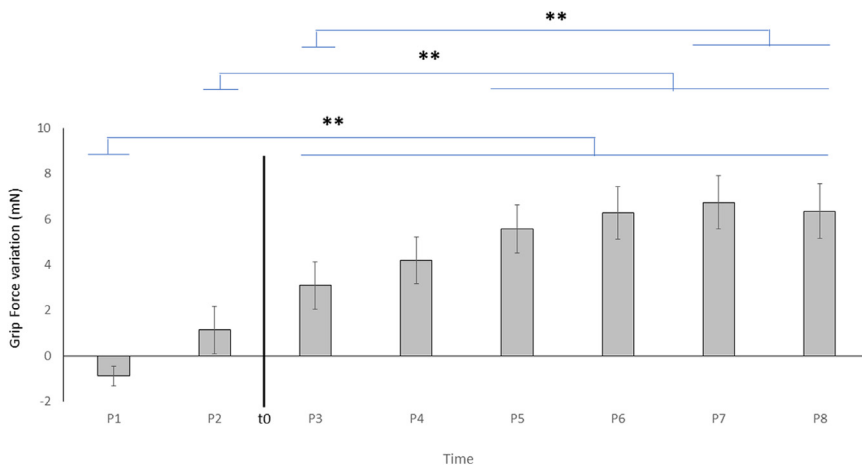
3.2. Effects of effector and intensity

There were no main effects of Effector on mean GF_v ($F_{(1,26)} = 1.984$, p = .171, $\eta^2 = .071$). Furthermore, the interaction Time and Effector did not reach significance ($F_{(7,182)} = 1.197$, p = .307, $\eta^2 = .044$) indicating similar patterns of mean GF_v through time, whether the Effector was the hand or the foot. Nevertheless, the interaction Intensity and Effector was significant ($F_{(3,78)} = 3.393$, p = .022, $\eta^2 = .115$ – see Fig. 4B). Tukey post hoc tests confirmed significant differences in mean GF_v between the Hand and the Foot trials in the Crush Intensity only (X_{mean} Hand = 4.08 mN, SE = 2.07 and X_{mean} Foot = 13.94 mN, SE = 2.11; p = .015). Mean GF_v were similar for Hand and Foot trials for all other Intensities (Wait Intensity: p = 1.000; Touch Intensity: p = .999; Move Intensity: p = .997).

To further investigate the nature of the effector differences, we computed slopes for the Middle and the High intensity conditions for each effector, and performed a repeated measure *t*-test. These results are presented in Fig. 6. No significant differences were found between the slope coefficients in both Middle (M = .025, SD = .017) and High (M = .026, SD = .030) intensity conditions for the hand effector (t_{25} = .193, p = .848). However, a significant difference was revealed between the Middle (M = .013, SD = .024) and the High (M = .037, SD = .037) intensity conditions for the foot effector (t_{25} = 3.588, p = .001).

3.3. Correlations between grip force, inhibition and imagery abilities

Our running hypothesis was that poor imagers would have weak inhibition abilities and would need more sensorial experiences in order to immerse within the simulation process. To test this hypothesis, we selected the mean GF_v obtained in the P5 and P6 time periods of the High Intensity action videos, epochs that contained the greater GF_v means. The accuracy and the vividness of both the Visual and Kinesthetic Motor Imageries were calculated via the Movement Imagery Questionnaire (MIQ). The inhibition abilities were evaluated using the BIS scores of the BIS/BAS questionnaire.

There was an absence of correlation between GF_v and the BIS inhibition score (P5: R = .037, p = .791; P6: R = .144, p = .295 – Fig. 7, *right*). Correlations were also none significant between the BIS scores and the motor imagery abilities (KMI: R = .178, p = .440; VMI: R = 161, p = .486). Results indicated that mean GF_v and the accuracy of KMI were not significantly correlated (P5: R = .009, p = .949, P6: R = .001, p = .994). A similar absence of correlation was observed between mean GF_v and the accuracy of VMI (P5: R = .124, p = .372; P6: R = .088, p = .807).

The vividness of both the Visual and Kinesthetic Motor Imageries were finally considered. Statistical analyses did not reveal a significant correlation between GF_v and the vividness of VMI (P5: R = .014, p = .920; P6: R = .071, p = .611). However, significant negative
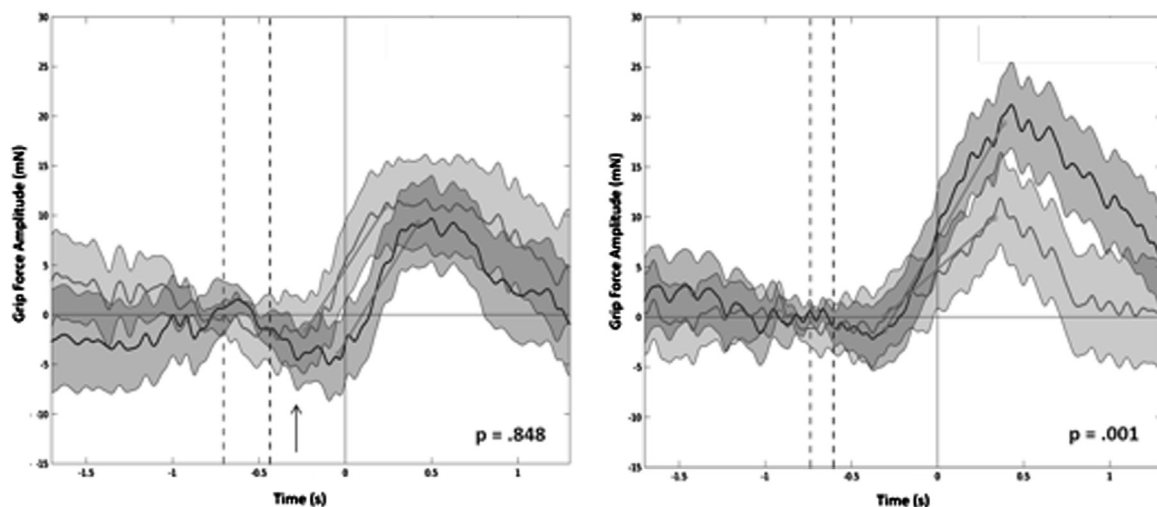
Fig. 6. Time courses of the mean grip force amplitude are presented as a function of time for the Move and Crush video types using the Hand (left panel) and the Foot (right panel) effector. The dashed lines reveal the moment of movement initiation of the effector in the Middle (*light grey*) and the High (*dark grey*) intensity conditions. The red straight line corresponds to the slopes in each condition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

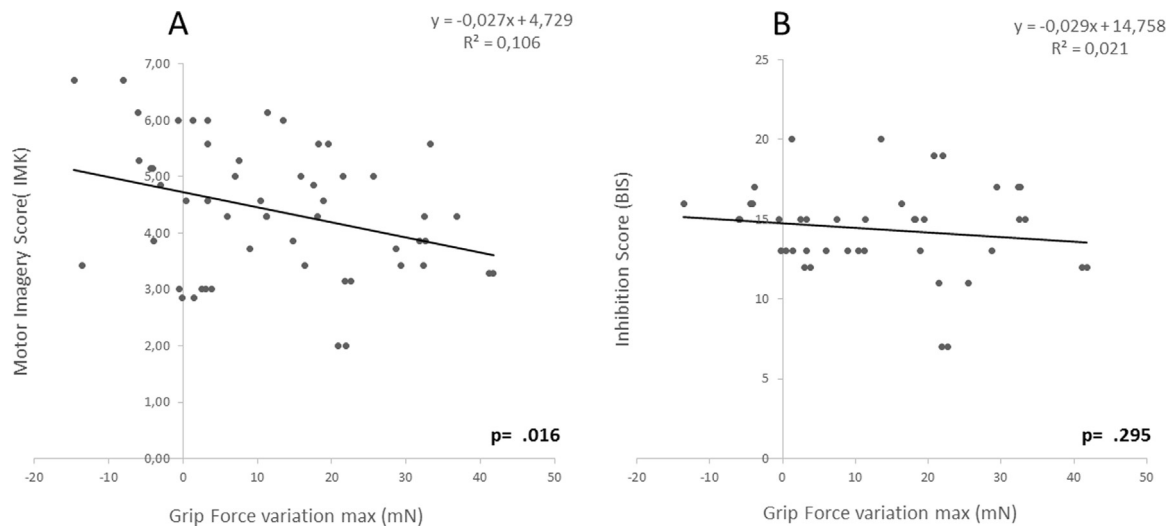**Fig. 7.** Illustrations of the correlation dispersion between grip force variations for the Crush High intensity action videos, during the Time period for which the greatest brain activity overflow was observed (P6). Panel A. Results revealing a significant negative correlation between the vividness of the Kinesthetic Motor Imagery (KMI) and the mean GF_v measured during the Time period of P6. The more a participant estimated that it was difficult to perform the motor imagery task, the greater the grip force was modulated during the time course of the action simulation process. Panel B. Results showing an absence of correlation between the BIS Inhibition scores (from the BIS/BAS questionnaire) and the grip force variations during P6, suggesting that the quantity of activity overflow to the motor system is not directly related to the cognitive inhibition abilities of the participants.

correlations were observed between the vividness of the KMI and the mean GF_v measured during both the Time periods of P5 (R = −.270, p = .048) and of P6 (R = −.326, p = .016 – Fig. 7, *left*). The more a participant estimated that it was difficult to perform the motor imagery task, the greater the grip force curves were modulated during the time course of the action simulation process.

4. Discussion

Electrical myographic activity (EMG) is a measuring technique that suffers from great variability. Hence, we opted here for the use of a highly sensitive grip force sensor in order to capture the micro-adjustments that take place in the muscles, as a peripheral consequence of the action simulation process. Developed and validated first in a language context (Nazir et al., 2017), the grip force paradigm was previously used to study how action simulation processes are involved in the understanding of action verbs contained in positive and negative sentences (Aravena et al., 2012). In the present study, we used the grip force paradigm to study the role of action simulation in the understanding of action videos, depicting a simple scene of a person interacting with an object either with the foot or with the hand. By synchronizing the force recordings and the video viewings, we describe here a simple behavioral paradigm that probes through millisecond-time, the quantity of brain activity that overflows from the motor cortices to the peripheral motor system during motor imagery. The findings reported here confirm that the amplitude of the motor simulation process is affected by the intensity of the scene: the greater was the intensity of the action between the effector and the object, the larger were the grip force variations as measured on the force sensor. Little grip force variations were observed in those trials for which participants did not engage in a simulation process namely when viewing no-action videos. Furthermore, through the fine-grained analysis of the grip force modulations, the importance of the time window around action goal was confirmed with less than a 500 ms delay for the brain overflow to have behavioral consequences on the peripheral muscular system. In the following section, we discuss the present findings in the view of proposing the grip force paradigm as a valuable method to rapidly test the involvement of motor cortices and of action simulation processes more generally, for human cognition in normal and pathological populations.

4.1. Temporal aspects of motor simulation

Action simulation is not instantaneous but is a phenomenon that takes time to unfold. The classical way to study action simulation is to use questionnaires to assess the vividness of motor imagery. This approach provides little information about the time-course of the cognitive processes involved in action simulation. In the present study, we used a grip force sensor that provided an online measure of the time-course of involuntary muscular contraction induced by the cortical overflow of motor cortex activity with a delay. After the control of gradual force drifts and noise, we clearly observed a modulation of grip force variations according to the development of the motor action presented in the video sequences. While no grip force variations were observed during the initial trial period (i.e., baseline), grip force started to increase 400 ms after effector-movement initiation, and peaked within 200–400 ms after effector-object contact (see Figs. 3 and 5). These timing properties were observed in all video intensities, suggesting a common neural process for the time-course of the action simulation phenomenon.

These results can be put into the context of direct neural recordings in non-human primates (Rizzolatti and Luppino, 2001). For example, Umiltà et al. (2001) reported that the activity of neurons in F5 premotor cortex were activated in macaques both when they performed and when they observed a human experimenter reach for and grasp an object. More interestingly, the same neurons fired also when the final part of the action was hidden, suggesting that mirror neuron activation is crucial for inferring action goal, through a motor simulation process. In humans, similar findings have been reported using different brain imaging techniques. For example, in a passive action observation study (Gangitano et al., 2004), participants observed a reaching-grasping task presented on a screen and were required to judge whether the hand moved above or under a square that was placed in the center of the screen. The MEPs induced by transcranial magnetic stimulation pulses were recorded in the first dorsal interosseus muscle (of the hand) to show that the amplitude of these MEPs are modulated and peak approximately one second after hand-object contact. In our study, thanks to the online streaming of GF modulations, it was possible to determine a narrower time-window as a function of action intensity. Indeed, the behavioral consequences of action simulation were observed between 600 ms (Crush actions) and 1500 ms (Touch actions) after the initiation

of limb movement (see table in Supplementary material 3). Because there is a direct correlation between speed and intensity of motor action, our data demonstrate that motor simulation is event-related not to the start of limb movement but rather to the end-point goal of the motor action, i.e., the moment of effector-object contact. Furthermore, our data suggests that the timing process within the synchronization window takes between 200 and 400 ms to develop fully, with greater slopes of GF increase as a function of the intensity of the action simulation process (see Fig. 6 - *right*). In fact, a 200–400 ms time-window for peak activity has been previously suggested in the literature. In a TMS study by Cavallo et al. (2014), participants watched action sequences created from 2 pictures of a right hand at rest. After a variable delay, a second picture presented the abduction of either an index or a little finger. TMS pulses were randomly delivered at 100, 150, 200, 250 and 300 ms after the onset of the second picture. Greater amplitudes in MEPs were recorded for the latter time-points of 200, 250 and 300 ms only. Based on their magneto-encephalography studies, Nishitani and Hari (2000, 2002) discussed that in addition to inherent transmission delays (estimation: 18–20 ms using TMS – Rossini et al., 1999), time is required for the cognitive information about observed actions to be transmitted from visual to motor areas via superior temporal, parietal and premotor cortex. Using a pure behavioral paradigm, our findings fit perfectly within the proposed 200–400 ms time-window, and further indicate that the action simulation process is time-stamped not to the start of movement itself but rather to motor goal, i.e., the moment at which the effector contacts the object that is to be manipulated.

4.2. Intensity aspects of motor simulation

The grip force sensor is a sensitive tool that can reveal the slightest micro-variations in finger grip when holding an object in precision grip between finger and thumb. In the present study, data from the force sensor was re-aligned to the critical moment of object-hand contact and the force curves were averaged. Such technique provided the means to demonstrate that action simulation is not an all or nothing process: action simulation as revealed by greater grip force variations is indeed stronger when looking at motor actions of greater intensities. While the Wait condition did not elicit more variations than the baseline measures, the other conditions (Crush, Move, Touch) showed contrasting amplitude variations – an objective finding that confirms and exceeds the subjective reports obtained using self-reported questionnaires.

Crushing an object requires greater effector acceleration in order to produce an action of greater intensity. For the actor, crushing movements will indeed engage more force and effort than simply moving or touching that same object. The energy and effort contained within the viewed-action triggered in our participants an implicit and significant modulation of finger force even if they thought to have stayed perfectly immobile throughout the viewing of the videos. These results are in accordance with the literature. In an fMRI study for which participants remained immobile throughout, Moody and Gennari (2010) presented sentences that conveyed different degrees of physical effort, varying from low effort ('pushing a chair') to a high effort ('pushing a piano'). The results revealed that two pre-motor regions (included in the action execution loop) – left inferior frontal gyrus and middle frontal gyrus – were more activated when listening to the high-effort than to the low-effort sentences. These findings suggest that the actions implied by the spoken sentences elicited an activation of the premotor cortex by activating the representations of the physical effort that would be experienced if producing the movement. In our study, the three different intensities elicited similar temporal changes in GF response patterns, but the slope of the GF patterns were affected proportionally to the degrees of energy/effort coded within the action videos. Thus, the GF-paradigm could be used as an indirect measure of the levels of activation of the premotor cortex when individuals are engaged in imagining performing body movements with distinct levels of physical intensity.

4.3. Effector specificity with intention or not to act

Effector-specify has been described in many brain-imagining studies. In an fMRI study of Buccino (2001), for example, participants watched videos that depicted object or non-object directed actions performed with different effectors (hand, mouth, foot) or videos of static effectors. Activations were revealed from ventral to dorsal areas in the premotor cortex corresponding to the observation of actions performed respectively by a mouth, a hand, and a foot. Therefore, there was a clear topographic shift congruent with the classical motor organization of brain regions (Penfield and Rasmussen, 1950). Moreover, in a linguistic study by Hauk et al. (2004), similar patterns of topographic activations of motor and premotor cortex were reported. Participants were instructed to read action words implicating the hand, the foot or the mouth. The mouth word activated bilaterally the inferior-frontal premotor areas, while the hand words activated the bilaterally middle frontal gyrus and the left precentral gyrus. Finally, the foot words activated foci in dorsal areas in left and midline pre- and post-central gyri. Hence, these patterns of results were also consistent with a somatotopic activation induced by action words in the motor and the premotor cortices. However, contrary to our predictions, we did not see an effector-specificity in the present study. Grip force variations in the hand have been reported by others when participants observed actions performed with different effectors, e.g., the foot or the teeth (Andersen et al., 1999; Komeilipoor et al., 2017). Such observations may be related to the fact that the action simulation process codes for body-movement intensity or intention. In the present study, the instructions to count the number of fruit/object items may have lead participants to imagine the intention behind the action, e.g., the hand is moving to crush the orange; the foot is moving to touch the cherry. Different results may have been observed if participants had been instructed to imagine concretely lifting or crushing the orange with the hand, as it is the case in the classic simulation studies. It is also the case that we rarely use the foot to touch a fruit. Hence, the context in which the effector-object interaction is set may mask a possible general effector-specificity effect.

A specific effector-effect was however observed in the Crush condition. When the effector was a foot (*dark grey* patterns in Fig. 4b), the grip force variations were proportionally greater in the Wait, Touch, Move and Crush trials. When the effector was a hand (*light grey* patterns), the grip force variations were also proportionally greater in the Wait, Touch and Move trials with however a clear tendency to a decrease in the Crush trials. We have previously mentioned the idea that when engaging in action simulation processes, one is imagining not only the intensity of the movement but also the intention coded within the observed motor actions. The limited grip force modulations reported in the present study in the Crush hand condition specifically may have been associated to the lack of willingness of the participants to engage fully in the action simulation process. Indeed, in a series of studies, we have shown how motor and social intention can be quickly detected while watching simplistic action videos (Lewkowicz et al., 2015; Quesque et al., 2013, 2016). Specifically, in the study by Lewkowicz et al. (2013), participants were invited to watch action videos of an actor moving an object with different social intentions. Results indicated that a time-window of 450 ms only was required for intention categorization above chance level. Early micro variations of movement kinematics can thus be used to quickly detect and infer the intention hidden within a moving limb. It is the case that performing an action of crushing a wooden object or a fruit with the hand is a painful experience; it is more painful to crush with the hand than with the foot. The observer knows and can imagine the sensorial consequences of effector-movement because of previous experiences in the real world (Zentgraf et al., 2011 for a review). The participants in the present study may have imagined performing the actions with their own body, and when anticipating the intention behind the movement, the pain underlying crushing the hard object with the hand may have lead them

to stop engaging in the simulation process. This halt in the action simulation would lead to weaker grip force variations after an initial increase in grip force modulation. Such patterns of results are hinted in the curves presented in Fig. 6 (see vertical arrow). Further studies are nevertheless required to pursue this hypothesis more specifically.

4.4. The impact of inhibitory and imagery abilities

Simulation theories propose that the brain structures normally used for executing goal-directed actions can be dedicated to simulate these actions internally, without executing them overtly (Jeannerod, 2001). Hence, action simulation processes would have the same content as overtly executed movements and use the same central brain mechanisms for processing, but an inhibitory mechanism would block their overt execution down-stream in the motor hierarchy. The study by Bruno et al. (2018) suggested such an idea by revealing that explicit inhibition of the simulation process had a direct impact on the amplitude of the MEPs. To gain a better understanding of the possible role of cognitive inhibition in the inter-individual differences in action simulation abilities, we included in the present study participants with different strength in cognitive inhibition as scored by the BIS score of the BIS/BAS questionnaire. On average, our participants had a BIS score of 14.38 (± 15.00), which indicates a sample of individuals with rather strong inhibition capacities in comparison to that reported in other studies (e.g., 21.35 ± 3.69 in Caci et al., 2007). Nevertheless, an absence of correlation was observed in the present study. It is possible that an inhibition process intervenes but that the questionnaire is not sensitive enough to reveal inhibitory involvement for motor simulation processes (Eriksson et al., 2016). Another possibility is that the inhibition process suggested by Jeannerod and colleagues is not of cognitive origin and that another type of inhibitory process would play the behavioral role of blocking motor output in the case of action simulation, as reported in the study by Bruno et al. (2018). Such debate is ongoing and a challenge for future studies will be to design behavioral material that can pinpoint the nature and properties of motor inhibition for simulation purposes.

Our running hypothesis was that poor imagers would need more sensorial experiences in order to immerse within the simulation process and as such, would be characterized by overall greater grip force variations than good imagers. This hypothesis was validated. A significant negative correlation was indeed observed between the vividness of the Kinesthetic Motor Imagery (KMI) and the amplitudes in grip force variations. These results are presented in Fig. 7 (*left*) and suggest that the more an individual estimated that it was difficult to perform the motor imagery task, the greater the grip force curves were modulated during the time course of the action simulation process. There may be a relation between the outflow recorded and the capacity to imagine oneself performing an action from a 1st person perspective. Participants with greater motor capacities may anticipate better the consequences of self-initiated actions but also of observed body movements and thus, disengage in the action simulation process in order to free cognitive resources for other tasks.

4.5. Potential transfer to clinical applications

A large literature of research in ageing populations has indicated a decline in motor imagery abilities in elderly individuals (Zapparoli et al., 2016; Malouin et al., 2010; Personnier et al., 2010; Skoura et al., 2008). In a neuro-imagery study conducted by Zapparoli et al. (2016), the ageing effects on motor imagery were investigated with a hand laterality task. Participants had to decide whether a rotated visual stimulus of a hand was illustrating the final posture of a left or a right hand. No group differences were found for task performance. However, more brain activations were observed in the elderly than in the young group of participants, suggesting stronger engagement in the action simulation process. The need of more cognitive effort to perform action

simulations is confirmed by studies measuring timing dissimilarities between young and older healthy adults. Indeed, in a chronometry approach, Personnier et al. (2010) proposed an experiment in which participants were instructed to perform or to imagine walking down a path. The younger group well respected the time of the performed and imagined walks, but it took more time for the older group of participants to imagine than to really perform the task, suggesting a distortion in the isochronicity principles and more generally, a deterioration in motor imagery capacities in normal aging. Such conclusions have been reached both using the chronometry approach (e.g., Skoura et al., 2005) and questionnaires (e.g., Malouin et al., 2010). However, are the differences reported between young and older adults due to a loss, or a change in the dynamics of the simulation processes? The use of questionnaires does not provide the means to disentangle between these two hypotheses. Using the vividness score, there is an indication that something is happening but the lack of dynamic insight weakens the possible interpretation of what is truly impaired in healthy and pathological aging. As such, the grip force paradigm may become an innovating tool to probe the action simulation process and provide valuable insights in the nature of the evolution of motor simulation deterioration in various pathologies, but also to reveal the impact of functional and physical re-education.

Context paragraph

Action simulation is the cognitive process that is involved in (1) the preparation of voluntary actions and (2) the anticipation of the effects of an action. We are interested in specifying the cognitive processes that are required to motivate a person to engage in regular physical exercise, and our recent studies are showing that action simulation performed before an activity can promote positive affective states by helping individuals better predict and sense the cognitive, physical and emotional consequences of the forthcoming physical session. However, an efficient behavioral approach was lacking in order to determine the power of the videos used to induce significant action simulation. Through the fine-grained analysis of grip force variations, we can now use the grip force sensor to pick up at the peripheral level, the cognitive-induced activity originating from the motor structures of the brain. By recording the brain activity overflow in real time when individuals are preparing to act, i.e., engaging in action simulation, we can adapt the material to promote pleasurable sports in sedentary and inactive individuals. More widely, the grip force paradigm is serving as an objective tool to study the importance of motor simulation and its dynamics across many fields of cognitive sciences.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2018. 04.026.

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