

D2.3

Results on prediction in dyadic action execution and observation - Phase I

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Introduction

This deliverable reports on the progress on the research conducted between M7-M24 of the EnTimeMent project with regards to the dyadic action execution and observation axis, focused on studies between interaction of two agents. The numbering of the studies reported herein, refers to the most recent version of deliverable D1.2 Research Requirements providing an update on the methodological background and know-how of the studies. Studies presented below are those that have either published or are in an advanced stage close to submission for publication (2.2.2, 2.2.3, 2.2.4, 2.2.6).

Dyadic interactions are the most primal of interactions between humans (i.e. infant-mother relationship), with different aspects of behavioral matching having profound developmental and psychosocial consequences such as acquisition of social skills (i.e. empathy), rapport building and expression of affiliation. Due to experimental and methodological constraints of multi-agent research, dyadic studies are a natural step forward from research focused on individuals, creating a more complete picture of the coupling that occurs not only with one's perception-action system, but predominantly with behavioural and physiological features displayed by the other side of interaction. In this context, the individuals are connected with each other, showing profound sensorimotor dependencies, influencing and absorbing information from each other in order to be able to cooperate, through means of anticipation and prediction. Thus, first of the presented projects (2.2.2) looks into the intricacies between observing an action of another person while performing a task, and interference between those two processes. Study results demonstrated that corticospinal inhibitory mechanisms that promote accurate motor execution are deeply affected by the co-participant's muscle-level state, estimated from action observation, which is a novel, neurophysiological perspective on underpinnings of behavioral matching. The second project (2.2.3) digs deep into the ability to anticipate motor behaviour on the other side of interaction and its links to the sensory cues available (visual, tactile). Importantly, study demonstrated that motor representations might vary between different agents, therefore interaction in cooperative tasks relies on adaptive, real time integration of sensory signals coming from the environment, which differentiates that prediction processes from the movements performed without other agents.

The third project (2.2.4) utilises principles of dyadic interaction as a canvas for modelling social behaviour of a mobile robot approaching a human agent. This study looked into perception of different trajectories and read out of social qualities such as

the intention of a robot by humans. It puts forward possibilities of using an imitation learning approach for programming most acceptable motor behaviour of a robot during interaction with human agents.

The final project (2.2.6) explored whether Individual Motor Signature (IMS), a unique for each person and relatively stable movement strategy in the environment, is potent of capturing mid-layer features such as emotional qualities. In this study an autobiographical recall is used as a mean for emotions induction prior to the dyadic motor improvisation task. The first results show that emotional qualities can propagate during interaction of two human agents and leave their imprints on agents' IMS.

Taken together, Phase I results reported herein pushed forward our knowledge about sensorimotor dependencies between humans during dyadic interaction by addressing multiple gaps in the body of research. Findings reported below emphasize the importance of including the social interaction aspect in the modeling of human motor behaviour, as it adds to our understanding of individual processes. Research roadmap for Phase II of the EnTimeMent project has been established (D1.2 Research requirements), which will push further the frontiers towards more comprehensive understanding of modeling human interaction, modulated by qualities such as emotion or intention, across multiple timescales.

2.2.2 Motor cortical inhibition during concurrent action execution and action observation

For a full description please see: Cardellicchio P., Dolfini E., Hilt P., Fadiga L., D'Ausilio A. (2020) *Motor cortical inhibition during concurrent action execution and action observation. Neuroimage, 208, 116445.*

Observing others' actions activates an extended parieto-premotor brain network, often referred as the Action Observation Network (AON), which is partially overlapping with the cortical network recruited for action preparation and execution (Giese and Rizzolatti, 2015; Hardwick et al., 2018). Sensorimotor activity during AO may support action-related perceptual processes (Avenanti et al., 2013). According to the predictive coding hypothesis, other's action sensory outcomes are compared to sensory predictions generated by the same hierarchical neural machinery for movement preparation and execution (Donnarumma et al., 2017; Friston, 2011; Friston et al., 2011). Perceptual discrimination and prediction of other people's actions may have a key role in supporting temporal and spatial interpersonal coordination (Pezzulo et al., 2018). We may indeed observe other's actions, to produce complementary responses in a turn-taking fashion (e.g., playing tennis) or to simultaneously coordinate our own

movements with those of others (e.g., when moving a heavy object together). However, the cortical response to new stimuli is influenced by ongoing activity in the same neural substrate (Silvanto et al., 2008). We can thus expect that temporal and spatial overlap of the neural processes subtending AE and AO produces functionally relevant interaction.

Nevertheless, little is known about the neurophysiological mechanisms subtending the interaction of concurrent AO and AE. Corticospinal excitability (CSE) modulation has provided direct neurophysiological evidence that passive AO activates the corresponding motor representations in the observer's sensorimotor system (Fadiga et al., 1995). These sensorimotor modulations are characterized by a fine temporal and muscle specificity (Fadiga et al., 2005; Naish et al., 2014; D'Ausilio et al., 2015) and are influenced by proprioceptive feedback (Varlet et al., 2017). However, we yet don't know whether and how a voluntary descending motor drive interacts with the concurrent observation of others' action.

Here we designed four experiments, to elucidate the neurophysiological mechanisms subtending the integration of AO and AE. In the main transcranial magnetic stimulation (TMS) study, participants were asked to keep the same isometric opened or closed hand posture, while observing an intransitive hand opening or closing action. The dependent measure was the length of the Cortical Silent Period (CSP) elicited from the Flexor Digitorum Superficialis (FDS) muscle. CSP is a corticospinal index of inhibition visible only during a tonic muscular contraction and following a TMS pulse. This GABA_B-mediated neurophysiological index has been associated with the voluntary motor drive (Tergau et al., 1999) and, in AE, is regarded as a marker of response selection (Davranche et al., 2007; Tandonnet et al., 2012).

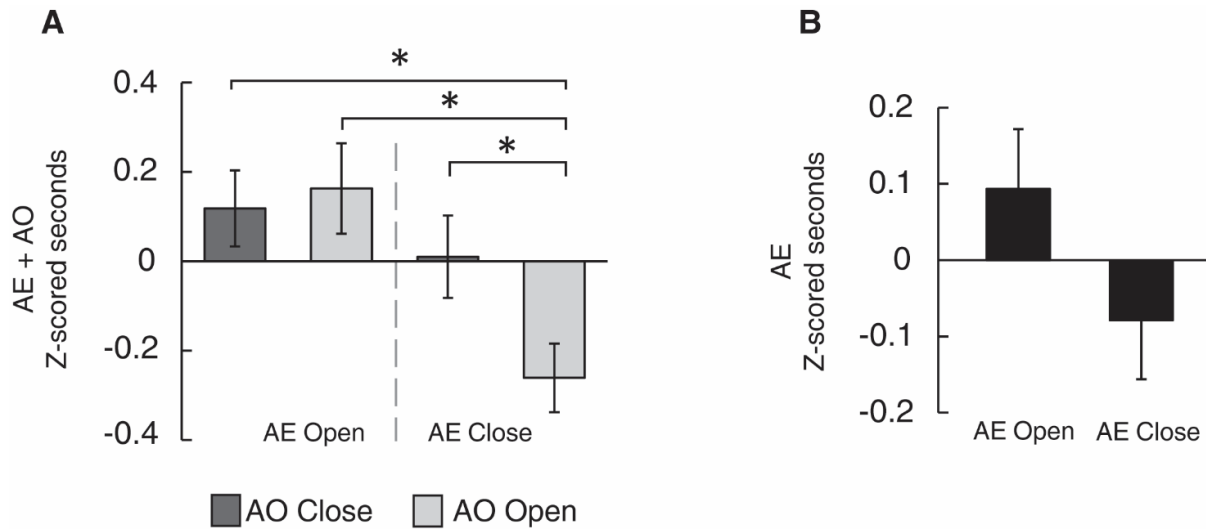


Figure 1: Results of the main TMS experiment. Panel A: Z-scored CSP duration during concurrent AE and AO. A reduction of CSP duration is shown during the execution of a closing action while observing an opening action. Panel B: CSPs during AE alone does not show any differences. Bars indicate the standard error of mean. Asterisks indicate significant comparisons.

Corticospinal inhibition decreased during mismatching executed and observed actions. In our main experiment, we show reduction of corticospinal inhibition only for the execution of hand closing actions while observing opening ones. The lack of symmetry (e.g. no effects for opening AE during closing AO) can be explained if we consider the function of the muscle recorded here. Although equally recruited in both actions (see first EMG study), the FDS muscle is instrumental in achieving hand closing but has only a postural role in opening, which is instead realized by recruiting forearm extensors (e.g. EDC). All experiments combined demonstrate that AE-AO mismatch is computed at the level of muscle recruitment and according to an agonist-antagonist mapping of actions. Critically, the functional contribution of muscles to a specific action seems to be the guiding principle in allowing modulation of corticospinal inhibitory circuits for AE-AO mismatching conditions.

The CSP measures supraspinal inhibitory activity in the motor system, at least in its late component (Fuhr et al., 1991; Inghilleri et al., 1993; Ziemann et al., 1993). CSP duration reflects motor cortical postsynaptic inhibition and is potentially mediated by GABA_B receptors, thus indexing the involvement of slow metabotropic-mediated inhibitory neural circuits (Ziemann et al., 2015). The monosynaptic spinal reflex (H-reflex), which provide a measure of spinal excitability (Bestmann and Duque, 2015), is facilitated before movement onset (Gottlieb et al., 1970) while it is reduced during passive AO (Baldissera et al., 2001). This latter study shows that spinal centers are suppressed during action observation, possibly to avoid unnecessary automatic action imitation. Conversely, AO induces a reduction of intracortical inhibition thus shifting the balance towards greater local excitation (Cardellicchio et al., 2018; Patuzzo et al.,

2003; Strafella and Paus, 2000). As a consequence, AO might constitute a source of neural noise interfering with the correct execution of actions, both at the cortical and spinal levels. Motor inhibition, with its tightly link to cognitive processes (Hilt and Cardellicchio, 2018; Wessel and Aron, 2017), could have a central role in enhancing signal processing, facilitating action execution and preventing early change detection signals from translating into behavioral distraction (Greenhouse et al., 2015; Wessel et al., 2019). For instance, when we execute an action (e.g. hand closing) every other action produced by the same effector should be suppressed (e.g. opening is suppressed to effectively execute a closing action). However, in a mismatching AE-AO condition, the observed action (opening), by activating the corresponding cortical representation in the observer (Fadiga et al., 1995), contrasts with its required attenuation. This mechanism of corticospinal disinhibition might explain the numerous evidence showing AO-AE behavioral interference (for a review see Cracco et al., 2018). Conversely, matching AO-AE may facilitate action selection and preparation thus explaining the automatic imitation tendencies for similar actions (Bisio et al., 2010; Heyes, 2011). More importantly, disinhibition does not emerge from mismatching action goals. Rather, attenuation of corticospinal inhibition is selective for the muscle that is functionally involved in the executed versus the observed action. Based on our results, mismatch seems to be computed in a muscle space whereby actions are mapped according to an agonist-antagonist representation. Our results offer a first demonstration that corticospinal inhibitory mechanisms promoting accurate motor execution are deeply affected by the co-participant's muscle-level state, estimated from action observation.

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2.2.3 Anticipatory postural adjustments during joint action coordination

For a full description please see: *Nogueira-Campos A., Hilt P.M., Fadiga L., Veronesi, C., D'Ausilio A., Pozzo T., (2019) Anticipatory postural adjustments during joint action coordination. Sci Rep, 9: 12328.*

Imagine a waiter lifting with his right hand a glass of wine on a plate he is holding with the left hand. The success of such a bimanual asymmetric task depends on the waiter capacity to counteract the upward perturbation induced by the unloading movement. In such a context, the central nervous system can anticipate movement consequences and produce anticipatory postural adjustments (APAs) (Hugon et al., 1982, Massion et al., 1999). APAs consist in using an efferent copy (Wolpert et al., 1997) of the motor command descending toward the lifting hand to prevent the disturbance exerted on the postural hand. When the two hands hold the plate and the glass, APAs on the postural hand start before the onset of the unloading action. If a reaching phase precedes the lifting, the visual feedback on the reaching could add to the efferent copy in anticipating the unloading. Whilst interesting, previous investigations did not provide the appropriate experimental context to understand how these two signals contribute to efficient bimanual interactions. Indeed, either subjects bimanually picked up objects with the two hands already positioned on the recording set up (Hugon et al., 1982; Dufosse et al., 1985; Paulignan et al., 1989; Ioffe et al., 1996; Barlaa, et al., 2011) or initiated the unloading by pressing a button (Diedrichsen et al., 2003). Further, when a reaching movement was included, the task was performed without visual feedback (Ng et al., 2011, 2013). The first goal of this study was to investigate the role of the visual feedback and to verify its potential additional value in the genesis of APAs by introducing a reaching phase preceding the bimanual load-lifting phase.

The investigation of how vision can impact on APAs may be essential if we extend the scope to the joint action scenario (Sebanz et al., 2006) where the waiter offers the glass to a guest. While APAs remain essential to the effectiveness of the dyadic interaction, the sole predictive signal is now provided by the visual cues about the guest's hand trajectory toward the glass. In the next step of the current experiment, we seek to verify if APAs, in joint action condition, might be driven by visual cues even in the absence of any efferent copy signal. Precisely, we want to verify if the existing predictive models for the control of the observer's (here the waiter) own action could anticipate in real time the effect of the guest's reaching, grasping and lifting movement. Accordingly, APAs are predicted because action observation elicits subthreshold sensorimotor activations analogous to those recruited during action execution (Fadiga et al., 1995; Gallese et al., 1996, Rizzolatti & Craighero, 2004). Importantly, this sensorimotor recruitment has already shown some degree of anticipation with respect

to the ongoing observed action (Borrioni et al., 2005) and has been proposed to be a key asset in allowing others' action prediction both in absence of any interaction (Avenanti et al., 2013, Urgesi et al., 2006) and during joint action conditions (Pezzulo et al., 2017).

The present study directed at these goals by applying a classical APA paradigm of quantifying motor prediction while wrist flexor and extensors muscle activities were recorded during a reach-to-grasp load-lifting task performed either alone (Self condition), or with the help of a partner (Joint condition) (Figure 2). The task was divided in three movement phases – reaching, grasping and lifting, where each one reflected the presence of different combinations of predictive signals – efferent copy, visual and somatic ones. Thus, since one of the key tenets of APAs is that motor behavior must be self-produced (Diedrichsen et al., 2003), we should find APAs independently of visual feedback in the Self condition, in which the task was executed alone. In this sense, running the task with eyes open or closed, should in principle produce identical results if visual feedback is not incorporated in the generation of APAs. In the dyadic scenario, APAs need to be implemented to engage safe and efficient joint action coordination. However, the absence of the efference copy signal puts the burden of anticipation upon a different set of signals. Only somatic (i.e. tactile cues from object-hand haptic interaction and force change during lifting) and visual input (i.e. hand reaching trajectory) may be used in this case. It is important to mention that somatic cues have in any case far less predictive power than visual ones as they are available only after object contact. Here, the task is also executed with eyes open and closed, so that in one case both somatic and visual cues are present, while in the other, only somatic signals are made available.

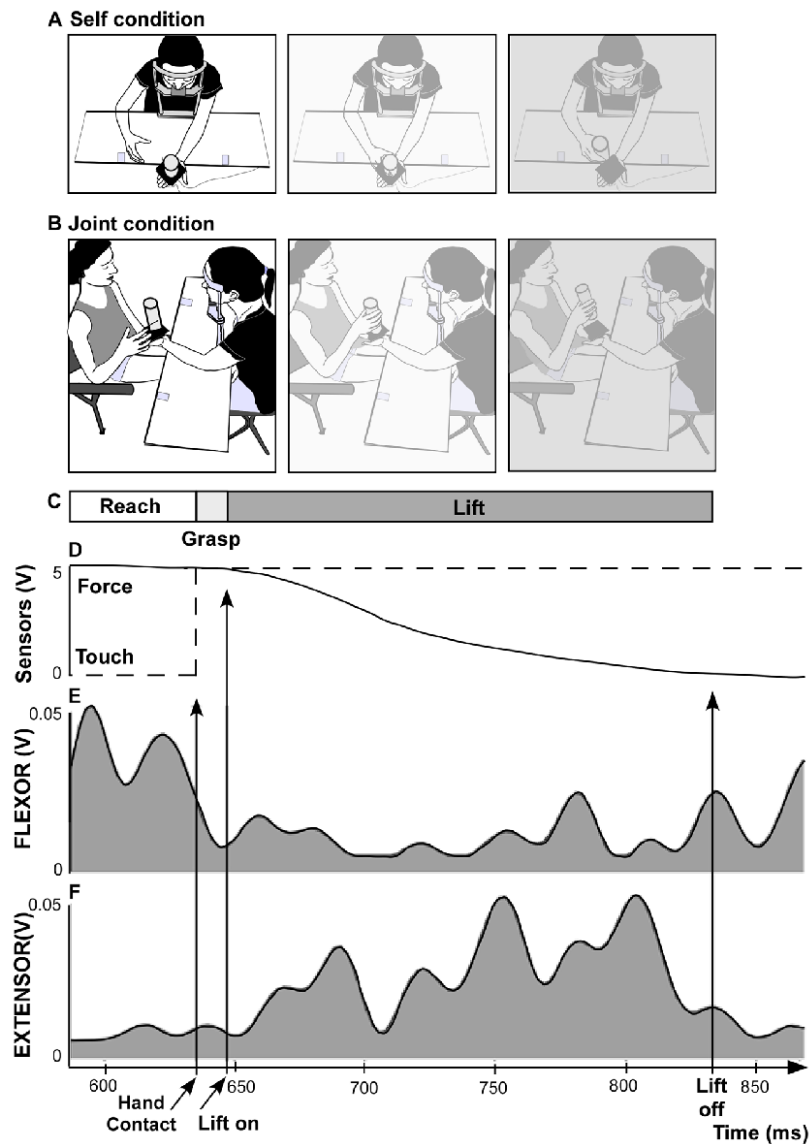


Figure 2: Experimental setup. (A) Self condition: frontal view of the carrier holding the object with his left hand and reaching (left), grasping (middle) and lifting (right) the object with his right hand. (B) Joint condition: Lateral view of the carrier (black dress) holding the object with his left hand, while his partner (gray dress) reach (left), grasp (middle) and lift (right) with his right hand. In all experimental conditions, the carrier had to keep his left arm flexed on the table with the wrist supinated holding the object in his hand. The bar situated below the pictures (C) represents the duration of the different phases of the task: reaching (white), grasping (light gray), lifting (dark gray) for a typical trial (Self condition with eyes open). These phases were determined based on touch and load sensors displayed below (D). The two lower panels show the muscle activity of wrist flexor (E) and extensor (F) muscles for the same trial. Vertical lines indicate the moment at which the object was touched (Hand contact), at which the lifting of the object started (Lift on) and at which the lifting ended (Lift off).

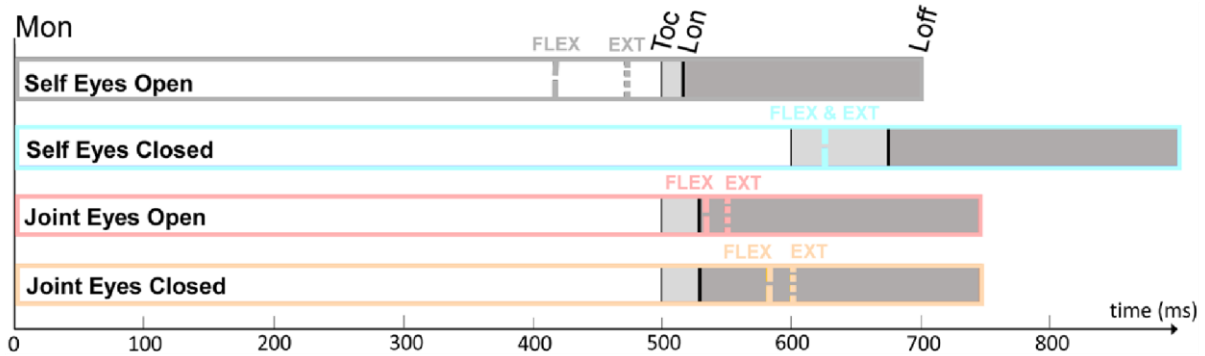


Figure 3: Illustration of the averaged onset of flexor (FLEX) deactivation and extensor (EXT) activation in function of the defined phases of the task. It depicts the time point in which the muscle adjustment started along the task for each experimental condition. Movement onset (Mon), Hand contact (Toc), Lift onset (Lon), and Lift off (Loff).

In Self condition with eyes open APAs investigation revealed clear forearm muscle changes and flexor deactivation starting about 80 ms before the hand touched the object (referring here to reaching APAs). In dyadic context, anticipated muscle changes were recorded after grasping onset. Longer lifting phase recorded in dyadic creates the temporal condition for a sensorimotor dialogue between the dyad, where the load bearing hand would assist the lifting hand. This dialogue, exclusively observable when the task is performed without any device or instruction artificially stabilizing the two hands, would create the temporal condition for controlling the task in the most insecure context. This agrees with the idea that APAs play a dynamic role in postural transition and provide additional force for the task goal achievement (Pezzulo et al., 2017; Pozzo et al., 1998, 2001; Stapley et al., 1999, Hodges et al., 1999). Notwithstanding, following the hypothesis that observed action is simulated with one's own motor repertoire (Schutz-Bosbach & Prinz, 2007; Jeannerod, 2004) in addition to behavioral data showing that perception and action planning are coded in a common representational medium (Prinz, 1996, 2007; Hommel et al., 2001) we predicted early grasping APAs in both dyadic and bimanual conditions. Specifically, vision of others' actions has been demonstrated to recruit both the motor (Caetano et al., 2007; Buccino et al., 2001; Hari et al., 1998) and the somatic system (Avenanti et al., 2007; Avikainen et al., 2002). These activations have been reported to anticipate the temporal deployment of observed actions (Rossi et al., 2002). Conversely, our results suggest that the observer's and actor's internal models did not fully overlap. Accordingly, APAs were only present as soon as visual input had been combined with tactile and force feedback. Thus, the visual cues from partner's action did not provide information to completely predict the dynamic disturbance to occur during the interaction at least in the context of the unloading task tested here, although in the dyadic with eyes open there is an anticipation compared to eyes closed (Figure 3). In summary, our results show that visual perception of action and associated motor resonance do not completely help internal variables adjustment during a classical load

lifting task performed by two agents. Rather, our findings demonstrate that in addition to self-motor representations, individuals adapt real time cooperation by continuously integrating sensory signals coming from various sources.

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2.2.4 Representing Human Movement in Dyadic Interactions: Impact of trajectory generation methods on viewer perception of robot approaching group behaviors

For a full description please see: *F Yang, W Yin, M Björkman, C Peters, "Impact of trajectory generation methods on viewer perception of robot approaching group behaviors", IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2020.*

Earlier work on generating safe and socially-acceptable paths for robots approaching groups of human subjects has typically assumed static scenarios with the subjects standing still, but in many cases, members of the group are quasi-dynamic, as they adjust poses and positions to accommodate the approaching robot (Kruse et al, 2013; Yang and Peters, 2019a). The question is whether past observations of approaching human subjects can be exploited to generate paths in response to the behavior of the group and whether this will lead to more socially-acceptable approach paths. We have thus conducted a series of experiments and tested three means of generating such paths.

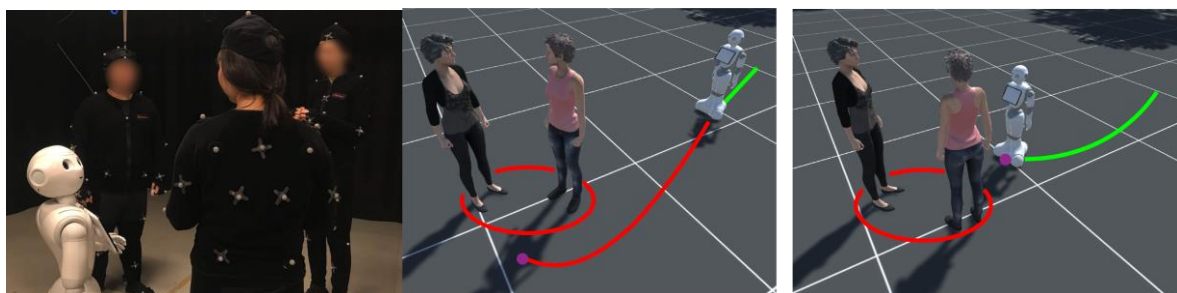


Figure 4: A Pepper robot approaching a group of participants during one of the recorded sequences (left) and two examples of possible approaches (center, right).

In the first condition (WoZ), a human operator is directly controlling the movement of the robot, using an egocentric camera placed on the forehead of the robot. A procedural model (PM) built on a model of the social-aware space (Yang and Peters,

2019b) is used to control the movement in the second condition. However, none of these conditions directly exploit past observations to guide the robot. This is unlike the third condition in which the robot is guided by a policy learned through imitation learning (IL), with the objective of producing paths that are inseparable from those that real human subjects would follow. Using a large set of recorded sequences of human approach behaviours with participants wearing motion-capture suits, the policy is trained through Generative Adversarial Imitation Learning (Ho and Ermon, 2016) with group movement analysis done using a Graph Convolutional Network- based framework developed within EnTimeMent (Yang et al., 2020). More details on this framework can be found in D3.5.

To evaluate the three alternative ways of generating robot trajectories, we asked 27 participants (18M:9F, 23-43 years old) to subjectively rate the robot approach behaviours and assess whether they were *polite*, *human-like*, and *safe*, using a 1-7 Likert scale. This was done using recorded videos, instead of live interactions. Studies have shown that the difference in rating between the two cases should be small (Kidd, 2003), but it is easier to conduct controlled experiments and replicate the robot behaviours using video recordings, especially during the Covid-19 pandemic. The camera viewpoint could, however, affect the ratings. Thus two alternative viewpoints were tested, an egocentric view as seen by one of the members of the group, and a perspective view overlooking the scene. We further looked at the difference between static and quasi-dynamic group behaviours, either with members standing still or moving in response to the approaching robot. For the evaluation, a total of 78 video clips were recorded, thereby representing all possible combinations of conditions.

Either the robot approaches the group directly (Figure 4, right) or indirectly (Figure 4, center) and in the egocentric view, there may be a difference between the left and right sides with respect to the camera view. For different combinations of egocentric/perspective views and static/quasi-dynamic groups, a summary of the subjective assessments is shown in Figure 5. For static groups, the results differ depending on from which side the robot is approaching.

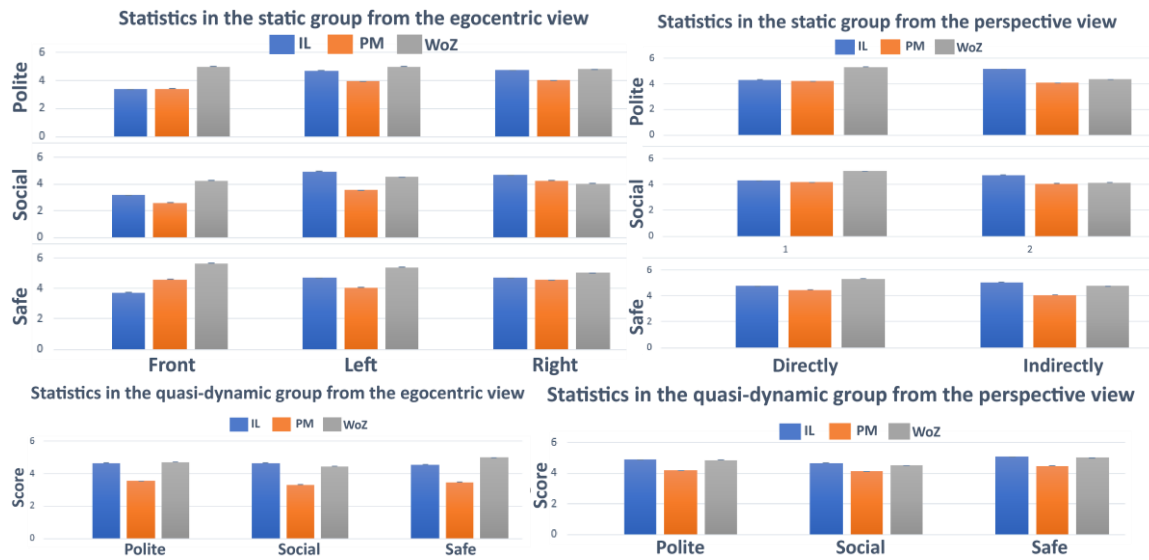


Figure 5: Subjective assessments for static (above) and quasi-dynamic (below) groups, using either egocentric (left) or perspective (right) camera views, depending on from which direction the robot approaches the group.

Using ANOVA F-tests with a significance level of 0.01, a number of conclusions can be drawn for the results. In the egocentric view with static groups, an approach in the front direction is regarded as least polite and sociable, but with no significant difference in safety. When approaching from the left or right sides, IL scores similarly to WoZ, both higher than PM. The same is true for quasi-dynamic groups in both views. In the perspective view, WoZ scores higher in both politeness and sociality, when the robot approaches directly, and IL when the approach is indirect. However, WoZ and IL perform similarly in terms of safety. One conclusion that can be drawn is that, using a set of earlier examples of human approach behaviours, imitation learning can be used to replace a human operator to control the approach of a robot, which is preferable from using a procedural model in terms of both politeness, sociality and perceived safety.

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2.2.6 DuoMotion

Several studies have focused on dyadic synchronization (e.g., Issartel et al., 2017; Schmidt & Richardson, 2008). Most of them have shown what are the biomechanics sources of synchronization. However psychological aspects also need to be taken into account in the motor interaction. For instance, if one partner is sad or happy it is possible that i) the quality of the synchronization would be impacted and ii) the motor signature of the dyad temporarily changed at multiple time scales. Finally, iii) motor signature of each emotion could be revealed. DuoMotion study aims to explore how two people are able to create a joint and improvised movement, following the paradigm of mirror game (Noy et al, 2011), while being induced with positive or negative emotion.

Participants were asked to improvise movements with their dominant hand in the horizontal axis, using a ball mounted on a string to create linear motion. In each trial participants were induced with different emotions (negative, positive or no emotion - neutral) via autobiographical recall method. Participants improvised movements under each emotional state in 3 different conditions: in Solo, Duo congruent (the same emotion was induced to the two participants) and Duo incongruent (different emotions were induced to each participant in order to observe whether there was an emotional contagion to one participant).

This study is still at the stage of data collection, but preliminary data from 13 dyads (n=26 participants) has been analysed as a part of a Master thesis within the EnTimeMent project and submitted for publication (Lozano-Goupil et al., 2020). As a main metric of the study, an individual motor signature (IMS) was extracted to i.) capture the subtle differences in the way each individual is moving, ii.) observe whether there is a change in IMS depending on the internally induced affective state (positive or negative to neutral as baseline) experienced by individual or their mirror game partner, iii.) quantify if there is a dyadic IMS during interaction that is specific to this particular pair of individuals. Previous research has demonstrated that IMS is a

time-invariant, robust and parsimonious measure of individual characteristic in movement (Slowinski et al., 2016, Coste et al., 2020). Little it is known however whether emotions can modulate IMS and how it is affected by interaction with another human presenting their own IMS during improvised, joint action tasks. Using similarity measures IMS were calculated for each participant in the tested dyad, Figures 6-9 depict preliminary data analysis.

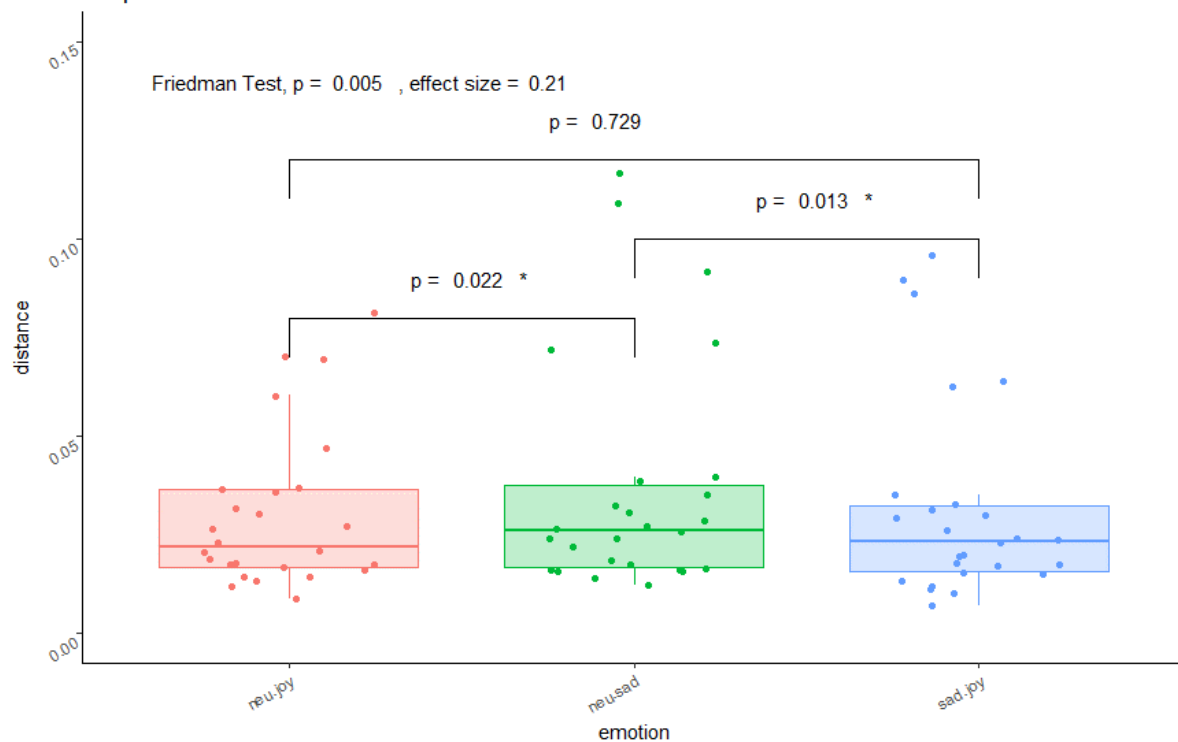


Figure 6 : Results of distances between the motor signatures of the three emotional conditions (Neutral, Sadness and Joy).

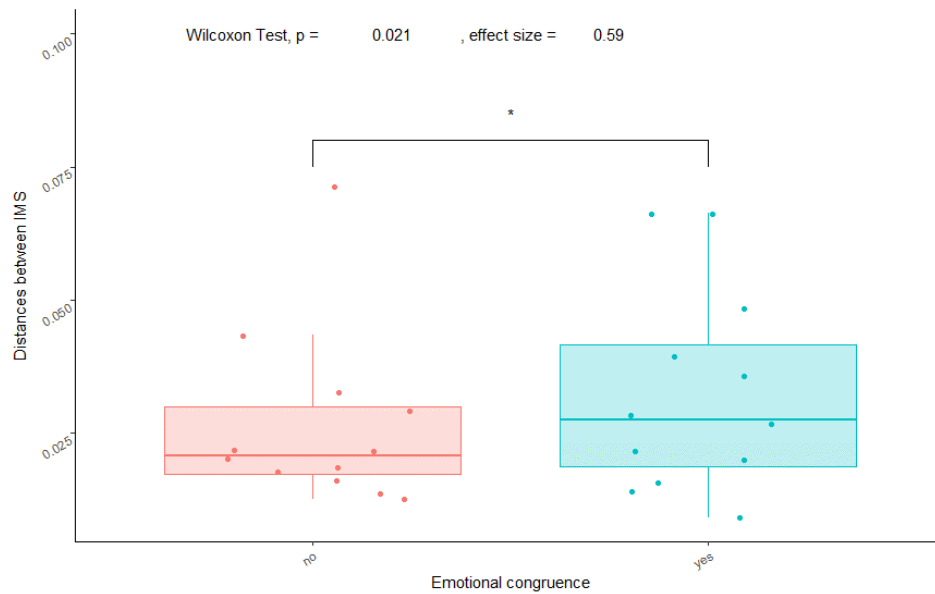


Figure 7: Results of distances between the motor signature of the condition « DUO *with* emotional congruence » and the condition « DUO *without* emotional congruence » for Joy, to evaluate the emotional contagion in a dyad.

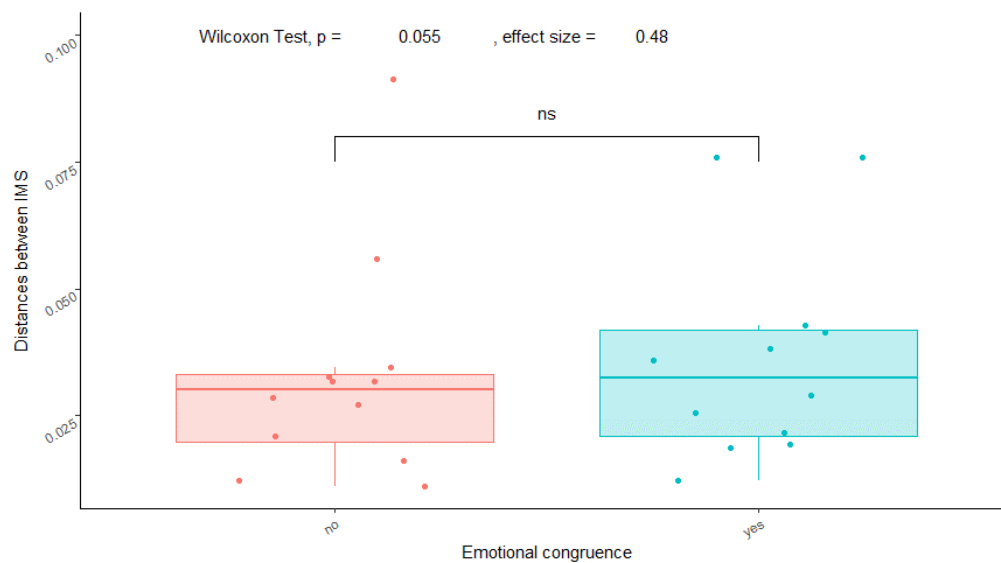


Figure 8: Results of distances between the motor signature of the condition « DUO *with* emotional congruence » and the condition « DUO *without* emotional congruence » for Sadness, to evaluate the emotional contagion in a dyad.

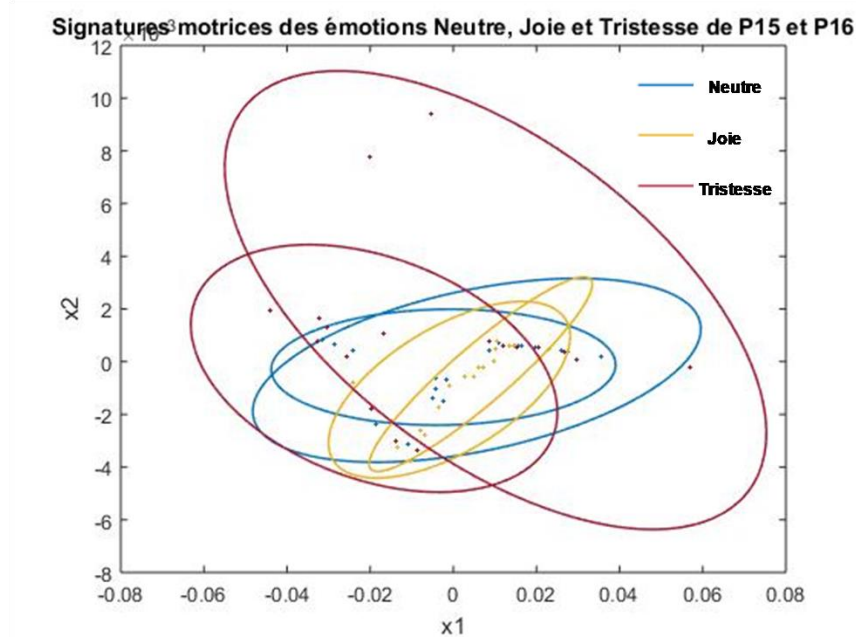


Figure 9 : Example of ellipses representing Individual Motor Signatures of two participants of a dyad for the three emotional conditions (Neutral in blue, Joy in yellow and Sadness in red).

We have found that induction of joy (positive) and sadness (negative) changes the IMS characteristics for participants. This leads us to thinking we can distinguish emotional IMS (EIMS), which perhaps shares some universal characteristics among people. Our preliminary data suggest that positive and negative emotional induction prior to the interaction modify dyadic motor interaction in terms of IMS and dyadic motor signature. When a positive emotion occurs within an incongruent dyadic interaction, the IMS of the participant induced with the neutral emotion converges to the IMS of the participant induced with the positive emotion. Our current line of interpretation is that IMS is susceptible to transfer of emotional qualities from other people by means of mimicry of actions. This phenomenon is accompanied by a real self-attribution of emotion (Chartrand and Bargh, 1999), a consequence of an emotional contagion by positive emotion (Prochazkova & Kret, 2017).

Results of the emotional induction showed that joy (as effect of positive induction, measured with the use of standardised questionnaire) and neutrality were effectively felt by all participants, especially when measuring emotions just after the induction task. Sadness was experienced less often as indicated by the responses on the mood questionnaire (PANAS). The preliminary data showed that we could identify changes in IMS that could be interpreted as EMS for positive emotion (joy) and for negative emotion (sadness), independent and different from the performance during neutral situation recall. Most importantly, during the incongruent dyadic interaction, the IMS of

the participant induced with the neutral emotion changed toward the IMS of the participant induced with the positive emotion qualities in movement, revealing a mimicry of gestures, which can be considered as the main component of emotional contagion (Prochazkova & Kret, 2017). Further analysis, when the dataset is complete, will inspect whether transient, temporal changes occur in IMS, leading to emotion signatures being nested in multiple timescales.

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