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Valeria Manera^{a,*}, Guenda Gaperi^a, Erika Rovini^a, Nadia Zeghian^a, Gramigna Laura Fiorini^e, Auriane Gros^{a,b,f}, Aurélie Mouton^{a,b,g}, Philippe Robert^{a,b,g} and Filippo

^a*CoBTek Laboratory, Université Côte d'Azur, Nice, France*

^b*IA Association, Nice, France*

^c*BioRobotics Institute, Scuola Superiore Sant'Anna, Pontedera, Italy*

^d*Department of Excellence in Robotics & AI, Scuola Superiore Sant'Anna, Pisa, Italy*

^e*Department of Industrial Engineering, University of Florence, Florence, Italy*

^f*Department of Speech Therapy, Université Côte d'Azur, Nice, France*

^g*Centre Mémoire de Ressources et de Recherche, Nice University Hospital, Nice, France*

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Abstract.

Background: Social apathy, a reduction in initiative in proposing or engaging in social activities or interest in mild neurocognitive disorders (MND). Current apathy assessment relies on self-reports or clinical attention is devoted to defining more objective, measurable and non-invasive apathy proxies.

Objective: In the present study we investigated the interest of recording action kinematics in a social reach-to-grasp task for the assessment of social apathy.

Methods: Thirty participants took part in the study: 11 healthy controls (HC; 6 females, mean age = 68.3 years), 19 subjects with MND (13 females, mean age = 75.7 ± 6.3 years). Based on the Diagnostic Criteria for Alzheimer's Disease, subjects were classified as socially apathetic (A-MND, $N=9$) versus non-apathetic (NA-MND, $N=10$). Sensory-motor actigraphy, a wearable sensor, was placed on their index finger, and subjects were asked to reach and grasp a can (individual condition) and pass it to a partner (social condition).

Results: In the reach-to-grasp phase of the action, HC and NA-MND showed different acceleration and time to reach the social versus individual condition. No differences were found for A-MND.

Conclusion: Previous studies showed the interest of recording patients' level of weekly motor activity for the diagnosis of MND. Here we showed that a 10-min reach-to-grasp task may provide information to differentiate socially apathetic subjects with MND, thus providing a tool easily usable in the clinical practice. Future studies are needed to better characterize these findings.

Keywords: Apathy, diagnosis, intention, motivation, motor activity, neurocognitive disorders, social behavior

INTRODUCTION

Apathy is a clinical syndrome characterized by a reduction in self-initiated, goal-directed behavior which is not driven by primary

*Correspondence to: Valeria Manera, CoBTek laboratory, Université Côte d'Azur, Nice, Institut Claude Pompidou, 10 rue Mollière, 06100 Nice, France. E-mail: valeria.manera@univ-cotedazur.fr.

the early stages of the disease progression [9] and is more frequent in amyloid- β positive patients [10]. The presence of apathy is associated with a faster cognitive and functional decline [11], representing a risk factor for the AD conversion in patients with MCI [12–14], and for dementia conversion in patients with small vessels disease, even after controlling for the effects of depression, age, cognition, and education [15]. Critically, preliminary evidence suggests that interventions targeting apathy in people with MCI (through repetitive transcranial magnetic stimulation, rTMS) may be effective to improve the global cognitive functioning [16], thus suggesting that identifying apathy early in disease progression—and putting in place early treatment options—could offer new opportunities for dementia prevention [17].

Apathy is a multi-componential syndrome and can be manifested across different dimensions [1, 18]. These include: behavior (e.g., reduced level of activity at home or work, or difficulty to accomplish tasks spontaneously, without being prompted); cognition (e.g., reduced interests in leisure activities, news or personal health and wellbeing); emotions (e.g., reduced feelings and emotional expressions in response to self- or other-related events); and social interactions (e.g., reduced social relationships with family and friends, homebound). There is evidence that the various apathy domains can be differently impaired over the time-course of different diseases, such as PD, AD, and frontotemporal dementia [19, 20], and that they contribute differently to individual cognitive profiles [21]. While the behavioral, cognitive, and emotional dimensions of apathy had been previously identified and extensively investigated in clinical ND (see [6, 19] for reviews), social apathy—the loss of social motivation—has been only recently recognized as a separate apathy dimension [1, 18, 22]. A preliminary study [23] suggested that

A self-report scale, the Apathy Evaluation Scale (AMI), has been recently developed to assess social motivation and social apathy in PD [22, 27], thus allowing for a clinical screening. However, questionnaires may suffer from subjectivity and bias. Indeed, self-report may be biased in the presence of cognitive impairment: questions about the behaviors, interests, emotions, and actions experienced in the last weeks may heavily rely, among others, on episodic memory, self-awareness, which are commonly impaired in patients with ND [28, 29]. The diagnosis of apathy and the clinical scales administered by clinicians to patients and caregivers remain the gold standard for apathy assessment. However, also these scales are subjective, and depends on the quality and quantity of information available [31], thus making the assessment, including the assessment of social apathy, strongly clinician-dependent. For this reason, giving attention is devoted to develop new scales that are objective, affordable, and reliable to complement the classical clinical assessment by clinicians with additional information for the diagnosis [17, 18]. As apathy is a multidimensional syndrome that manifests across different behavioral, social (verbal and non-verbal) and cognitive impairments, no index, in isolation, can capture apathy as a whole. Rather, the idea is to develop objective indexes that capture different dimensions and can be used, in combination with the classical clinical assessment, for an objective apathy assessment [32]. New technologies are offering novel ways to develop customizable and easy-to-use scales, allowing to quantify not only the severity of the apathy but also neuropsychiatric s

catatonic schizophrenia [42]), they are considered a reliable index to complement apathy assessment in patients with ND [39]. However, measuring the level of activity during a long timeframe to assess apathy is not always feasible in clinical practice.

In the present study, we investigated if assessing motor parameters during a short reach to grasp protocol using a non-invasive wearable device can provide relevant information to distinguish socially apathetic versus non-apathetic subjects with MND, thus providing additional elements for the assessment of the non-verbal aspects of social apathy in this population. The idea to employ this research protocol for social apathy assessment derived from three considerations. First, in healthy controls, action kinematics are sensitive to the social versus individual context in which the actions take place. Several previous studies showed that social intentions can influence action planning and execution: if we grasp an object to hand it to someone (social intention), the kinematics of the reach to grasp action is different from what observed when grasping the object to put it on a base (individual action), even if the object and its initial and final positions are exactly the same [43–47]. Specifically, both the kinematics of the reach-to-grasp phase (amplitude of maximum grip aperture and the speed at which the hands open, and movement smoothness) and the place phase (point of maximum trajectory height, peak velocity and time to peak velocity, movement smoothness) indicate a more careful approach in the social condition compared to the individual condition, thus suggesting a modulation of action kinematics based on the prior intentions. Second, this modulation of action kinematics based on the social versus individual context seems disrupted in patients with impairments, among others, in social motivation, such people with PD. Straulino and colleagues [48, 49] employed the very

on translating social intentions into action patterns in PD patients, thus suggesting that related circuits may impact motor planning and action kinematics. Third, action planning mechanisms implied in goal-directed actions and motor sequences are largely overruled in the case of motivated behavior [6, 50–54], suggesting a modulation of reach-to-grasp planning based on prior intentions and social context that relies on a complex neural network involving hierarchical structures in the parietal and frontal cortex modulated by the activity of the dopamine system [50–55]. Dysfunctions in these networks lead to deficits in motor planning and execution observed in several different pathological conditions.

In order to verify whether motor parameters of action kinematics in a social versus individual context can be used to implicitly assess basic social intentions of social apathy in ND, here we investigated in older healthy adults and patients with MND, with and without social apathy modulation, action kinematics based on the social versus individual context. Employing the previously described protocol, subjects were asked to reach and grasp an object in two conditions: an individual condition, in which the object was grasped and then placed on a base, and a social condition, in which the object was grasped and then passed to the experimenter. In the classical optoelectronic motion analysis system, here we asked subjects to wear on the back of their dominant hand the SensR device, a small, light, and easy to use, and thus more suitable for non-laboratory settings. Given the lack of force and control required in simple, naturalistic actions as object grasping is usually performed in patients with MND [56], we expected only minor differences between healthy controls and subjects with MND.

49], kinematic action modulation may be impaired in apathetic MND subjects, resulting in fewer differences in action kinematics (movement velocity and acceleration/smoothness) between the individual and the social condition, especially in the reach-to-grasp phase, which is identical between the individual and the social conditions.

MATERIALS AND METHODS

Participants

Thirty participants took part in the study. These included 11 older healthy controls (HC; 6 females and 5 males, mean age = 68.3 ± 10.5 years) and 19 subjects diagnosed with MND based on the DSM-5 [57] (13 females and 6 males, mean age = 75.7 ± 6.3 years; see Table 1). All participants reported to be right-handed. Participants were recruited at the Memory Center (CMRR) of Nice University Hospitals (CHU of Nice, France) and at the CoBTeK research lab of the Université Côte d'Azur in the context of

motor impairments. Healthy controls were recruited at the CMRR among the participants who were subjects that came for a consultation for a clinical sign of cognitive impairment, and not for a clinical concern. A brief screening (including a cognitive test) was performed to ascertain the absence of cognitive decline. The study was performed in accordance with the Declaration of Helsinki approved by the National Ethical Committee of the French Republic (Protection des Personnes - on 15/04/2019-A00342-55). All participants gave their informed written explanations on the study procedures and provided their informed consent before taking part in the study.

Clinical assessment

Based on the Diagnostic Criteria for MND [57], participants in the MND group were classified as 'socially apathetic' (A-MND; criterion "Interaction" present, N = 9) and 'not socially apathetic' (NA-MND; criterion "B3 –

Table 1

Socio-demographic and cognitive variables in healthy controls (HC), participants with minor neurocognitive disorders (NA-MND), and participants with minor neurocognitive disorders with social apathy (A-MND). The presence of apathy was assessed on the Diagnostic Criteria for Apathy, social dimension (B3; [18])

	HC (n = 11)	NA-MND (n = 10)	A-MND (n = 9)
Female, n (%)	6 (54.5%)	7 (70.0%)	6 (66.7%)
Age (y), mean $\pm$ SD	68.3 $\pm$ 10.5	74.2 $\pm$ 7.2	77.4 $\pm$ 4.9
Level of education, n (%)			
Primary	1 (9.1%)	1 (10.0%)	0 (0.0%)
Secondary education	3 (27.3%)	5 (50.0%)	5 (55.6%)
Higher education	7 (63.6%)	4 (40.0%)	4 (44.4%)
MMSE, mean $\pm$ SD	29.3 $\pm$ 0.9	26.4 $\pm$ 2.9	25.6 $\pm$ 3.0
AMI – Total score	1.2 $\pm$ 0.4	1.0 $\pm$ 0.4	1.6 $\pm$ 0.4
AMI – Social Motivation	1.4 $\pm$ 0.7	1.1 $\pm$ 0.5	2.2 $\pm$ 0.6
AMI – Behavioral Activation	1.1 $\pm$ 0.6	0.7 $\pm$ 0.4	1.6 $\pm$ 0.9
AMI – Emotional Sensitivity	1.4 $\pm$ 0.6	1.2 $\pm$ 0.5	1.1 $\pm$ 0.5

MMSE, Mini-Mental State Examination; AMI, Apathy Motivation Index. ^aKruskal-Wallis test. ^b χ^2 test.

16 g), a 3D digital angular rate sensor (full scale: $\pm 245/\pm 500/\pm 2000$ dps) and a 3D digital magnetic sensor (full scale: $\pm 4/\pm 8/\pm 12/\pm 16$ gauss). It is based on an ARM®Cortex™-M3 32-bit STM32-F103 microcontroller (STMicroelectronics, Italy) which acquires, filters and stores data at a frequency of 50 Hz. Further details about the instrument can be found in [46, 47].

The reach-to-grasp task and procedures

The subjects were asked to wear SensRing on the proximal phalanx of the index finger of the right (dominant) hand. Participants were sitting in a quiet room, in front of a rectangular table with the hand in the starting position marked with a blue rectangle, 3 cm away from the edge of the table in a midsagittal position, 15 cm away from the midsection. A closed 150 ml drink can (diameter = 5 cm, height = 8.5 cm) was positioned on the table in front of the participant at 21 cm from the hand starting position along the midsagittal plane (object position marked with a yellow square). After 5 s of acquiring the baseline static position (with the wrist and little finger touching the table, hand palm facing the participant's chest, fingers slightly bent and touching the thumb), a tone signaled to the participant to start the task. Participants were asked to reach and grasp an object in two conditions, adapted from [43]. In the Individual condition (IND), subjects had to reach the can, grasp it, and put inside a cup (diameter = 7 cm), placed on the table and located 28 cm at the right side with respect to the initial position of the can (position marked with a green rectangle). The experimenter (a 25-year-old female) seated to the right side of the table with her hands hidden below the table (see Fig. 1a). In the Social condition (SOC), subjects had to reach the can, grasp it, and pass it to a partner. The experimenter,

Fig. 1. Schematic representation of the experimental setup. The subject wore the SensRing on the proximal phalanx of the index finger of the dominant hand. The subject sat at a table with the hand in the starting position. In the Individual condition (a), he/she grasped the cup. In the Social condition (b), he/she grasped the cup to offer it to a partner. The position of the hand on the table and the position of the cup were identical.

who was also the action partner, sat on the left side of the table with the hand reaching for the target position as in the IND condition. The experimenter sat on the right side of the table, with fingers simulating a container (ready to the cup) ready to close the fingers when it reached the hand (see Figure 1). The experimenter's hand was completely stationary until the subject's hand reached it. When the subject put the hand into the experimenter's hand, the experimenter closed the fingers around it. The experimenter's hand never moved to the target position, and her fingers closed only at the very end of the action, to simulate the 'receiving the object' action. In both conditions, the action sequence was repeated 10 times. Each subject performed 20 trials, divided into two blocks of approximately 5 to 10 min. After each block, the experimenter repositioned the card to the next target position. The order of administration of the two conditions was randomized across subjects.

Inertial data acquired with SensRing were stored and offline processed by using MATLAB R2018a (The MathWorks, Inc., Natick, MA, USA). Triaxial accelerations and triaxial angular velocities, provided by the accelerometer and gyroscope, were pre-processed with a fourth-order low-pass digital Butterworth filter using a 5 Hz cut-off frequency to erase high-frequency noise. Custom made algorithms were applied to extract characteristic times aimed to distinguish between the reaching phase (RG), from the beginning of the action to the grasping of the object, and a placing phase (PL) from the grasping of the object to reaching the final position. Precisely, angular rates around the dominant axis were used to divide the signal. For each trial, a set of kinematic parameters was obtained from acceleration and angular velocities of the SensRing (see). All the kinematic parameters were calculated both in the RG and the PL phases, except for the reaction time, and the amplitude and the time of maximum hand excursion that were measured during RG phase only. In total, 15 features were extracted for each trial (9 for the RG, 6 for the PL phase) (see). Some kinematic parameters were chosen because they may be relevant to investigate differences in the baseline motor performance between healthy controls and MND subjects, such as reaction time, execution times and movement duration [48, 60, 61]. Other parameters were selected because, as previously demonstrated, they are sensitive to variations in the action context (social versus individual), such as the amplitude of peak velocity during both the RG and the PL phases, with the corresponding time instant, the amplitude of maximum aperture of the hand during the reaching phase with its associated time instant [43, 45], and the movement smoothness and variability [46, 47] in the RG and PL phases.

For all the analyses, a p -value ≤ 0.05 was considered as statistically significant. Statistical analyses were performed using IBM SPSS Statistics (version 25.0, IBM Corp., Armonk, NY, USA) and MATLAB R2018a (The MathWorks, Inc., Natick, MA, USA) to compute *post-hoc* corrected tests and non-parametric correlations.

RESULTS

Clinical and demographic characteristics

Clinical and demographic characteristics of the MND (A-MND), non-apar MND, and HC are presented in Table 1. No significant differences in the three groups did not differ significantly for age ($\chi^2_{(2)} = 4.24$, $p = 0.120$), gender ($\chi^2_{(1)} = 0.741$), and education ($\chi^2_{(4)} = 2.6$). No significant differences were found concerning the level of cognitive functioning, as revealed by the MMSE score (Kruskal-Wallis $\chi^2_{(2)} = 10.0$). Specifically, significant differences between the three groups were found for subjects with MND (NA-MND, $p = 0.020$) were found, but not for subjects with NA-MND and A-MND ($p = 0.020$) and A-MND groups concerning the global level of impairment of cognitive functions, as revealed by the FIM score (Mann-Whitney $U_{(2)} = 40.5$, $p = 0.731$). No significant differences across groups were found for the MMSE score ($\chi^2_{(2)} = 8.85$, $p = 0.012$) and the FIM total score (FIM subscale score ($\chi^2_{(2)} = 13.1$)). Specifically, as expected, A-MND subjects had significantly lower scores compared to NA-MND subjects (FIM total score, $p < 0.001$; AMI – Social Motivation, $p = 0.042$). No significant differences were found between healthy controls and MND subjects (FIM total score, $p = 0.042$). No significant differences were found between healthy controls and MND subjects (FIM total score, $p = 0.042$).

(AMI – Total score, $p=0.266$; AMI – Social Motivation, $p=0.233$). For participants in the A-MND group, impairment in social interaction dimension (B3 in the Diagnostic Criteria for Apathy) was associated to impairment in the B1 dimension (Behavior/Cognition) in 4 participants, and with impairments in B2 dimension (Emotion) in 1 participant, for a total of 5 out of 9 participants that meet the full set of Diagnostic Criteria for Apathy [18].

Movement-related parameters

Intergroup analyses

In subjects with MND, motor impairments are much less common than in PD, and we excluded from the study participants with motor problems (see Participants section). However, there is evidence that advanced motor parameters reflecting motor planning and control may vary between healthy subjects and people with cognitive impairment, for instance in the context of dual tasks [56]. In order to investigate the existence of baseline differences in the motion-related parameters across groups in a reach-to-grasp

task, we submitted each extracted parameter to a two experimental conditions to subject analyses.

For the *individual condition*, the intergroup comparison between the three groups revealed no significant difference of the group on the skewness of the acceleration in the phase ($Skew$, $\chi^2_{(2)}=7.44$, $p=0.024$). Specifically, skewness was significantly lower in HC compared to A-MND participants, indicating that they get a negative value of skewness, reflecting a wider variability for the acceleration during the movement with respect to a symmetrical distribution shown by the other groups. Comparisons between NA-MND and A-MND were not significant. A significant difference was also found in reaction times ($p=0.039$), with A-MND participants being significantly slower than HC ($p=0.041$). This finding is in line with the apathy literature suggesting that they have often deficits in action initiation.

For the *social condition*, the intergroup comparison across groups was the time

Fig. 2. Graphical representation of significant parameters ($*p<0.05$) at the inter-group analysis (A-MND, NA-MND, IND, SOC). Error bars represent the standard error of the means.

kinematics can be found between the individual and the social conditions [48, 49]. To explore the existence of differences in the kinematic parameterization depending on whether the action was performed with the intent of acting individually or socially, we compared the 15 kinematic parameters (listed in) in the individual versus social condition in each group in both the reach-to-grasp phase (which is identical in the two conditions) and the place phase (in which the experimenter's hand and the cup pose slightly different action constraints). Correlations among the different kinematic variables are reported in the Supplementary Material (Supplementary Tables 1–4).

Reach-to-grasp phase

In the HC group, paired-sample Wilcoxon test showed significant differences between the individual

implies a longer deceleration phase. In the social condition, thus a more careful action to place the object into the partner's hand. This difference between the individual and social condition for A-MND was reaction time ($p=0.017$), which was longer in the individual than in the social condition.

Place phase

In the HC group, significant differences were found on the rate of change of the acceleration vector ($RmseJ$, $Z=-2.76$, $p=0.006$), the peak velocity ($Kurt$, $Z=-2.85$, $p=0.004$), as well as the peak velocity (V_{peak} , $Z=-2.93$, $p=0.003$); similarly to the reach-to-grasp phase, acceleration and velocity were higher in the individual condition compared to the social condition.

Fig. 3. Graphical representation of significant parameters ($*p < 0.05$) at the intra-group analysis (IND, SOC) for the reach-to-grasp phase across three groups: A-MND, NA-MND, HC). The reported parameters refer to the reach-to-grasp phase. Error bars represent the standard error of the mean.

Fig. 4. Graphical representation of significant parameters ($*p < 0.05$) at the intra-group analysis (IND, SOC) for the NA-MND, HC). The reported parameters refer to the place phase. Error bars represent the standard error of the mean.

suggesting a more careful approach when handing the object to another person. However, the total execution time was longer in the individual compared to the social condition (T , $Z = -2.31$, $p = 0.021$). This is most probably due to the fact that the object final position (the cup) required a more precise gesture for object positioning compared to passing the object to the partner, who closed the hand to grasp the object when it touched her hand. Similar results for acceleration and velocity were found for NA-MND participants, showing higher rate of change of the acceleration vector ($RmseJ$, $Z = -2.70$, $p = 0.007$), kurtosis ($Kurt$, $Z = -2.60$, $p = 0.009$) and peak velocity (V_{peak} , $Z = -2.80$, $p = 0.005$) in the individual compared to the social condition. In the place phase, significant differences on the same parameters were also found for A-MND participants, who showed a higher rate of change of the acceleration vector ($RmseJ$, $Z = -2.07$, $p = 0.038$), kurtosis ($Kurt$, $Z = -2.31$, $p = 0.021$) and peak velocity (V_{peak} , $Z = -2.55$, $p = 0.011$) in the individual compared to the social condition. Intergroup analyses suggested that the mean differences between individual and social condition regarding the amplitude of peak velocity were significantly different across groups ($\chi^2_{(2)} = 10.56$, $p = 0.005$). Specifically, differences in peak velocity between conditions were significantly bigger for HC ($p = 0.003$) and NA-MND ($p = 0.008$) compared to A-MND. No significant difference in the magnitude of any acceleration parameter across groups was found (all $ps > 0.05$).

DISCUSSION

Social apathy, a reduction in initiating or engaging in social activities, is very common in people with MND. Clinical scales exist so far to assess social apathy [22, 62]. It is thus important to develop rapid, objective assessment tools for clinical practice to complement theoretical approaches. In the present study, we showed that measuring action kinematics during a reach-to-grasp social task to provide insight into non-verbal aspects of social apathy in MND. Participants were asked to perform a reach-to-grasp task to put it in a cup (individual condition) or to put it in a cup (individual condition) to a partner (social condition) [43]. Action kinematics were measured during the reach-to-grasp and the place phases with a motion capture system [46, 47]. Prior social intentions of participants when we perform actions: when grasping an object to put it to another person, the action kinematics during the reach-to-grasp and the pass phases were different from those observed when grasping an object to put it in a container [43]. Consistent with previous findings [48] and our hypothesis, intra-group analyses suggested that MND subjects differentiated, at the individual level, the individual from social reach-to-grasp task into the ‘reach-to-grasp phase’, and in the place phase. Specifically, in the reach-to-grasp phase, the individual with NA-MND showed a more

as the experimenter closed her fingers to grasp the object after the subject put it in her hand, the placing action could be slightly less precise in the social condition compared to the individual condition, in which the subject was the only responsible for placing the object in the final position. Critically, A-MND subjects did not show any difference in the acceleration and movement profiles in the reach-to-grasp phase, suggesting that movements were unaffected by social intentions. The only significant difference between the individual and the social condition for A-MND was reaction time, which was longer in the individual versus social condition. This suggests that people with social apathy took longer to initiate the action in the individual condition, which could be possibly due to higher demands in action control in the object positioning, requiring a more careful action planning before action initiation. Significant differences between the individual and the social conditions were observed for A-MND in the ‘place’ phase, with lower velocity and acceleration profiles in the social compared to the individual condition. These differences were also found in HC and NA-MND; however, differences in peak velocity between the individual and the social condition were significantly bigger in HC compared to A-MND, suggesting that action modulation based on social intentions in the place phase, even if present in A-MND, was smaller than in HC. The reduced modulation of action kinematics in A-MND subjects converges with results collected using the same experimental paradigm in PD patients. Indeed, PD patients in the ‘off’ l-Dopa medication state were found to be unable to kinematically differentiate between individual and social conditions [48, 49]. Given that PD patients show motor impairments and apathy, and that both symptoms are sensitive to l-Dopa medication, in PD patients it is hard to disentangle the roles of apathy and basic motor impairment

more variability in acceleration than in the individual condition, leading to less smooth movements. Finally, in the social condition, peak velocity was reached earlier, indicating sharper movements with respect to HC and NA-MND. No main differences between groups were found for action duration, suggesting that HC and subjects with MND showed similar motor performance in basic reach-to-grasp sequences. It is likely that more complex action kinematic parameters would have been affected using more complex and/or unusual actions (e.g., speeded finger tapping), or under a higher cognitive load, as those employed in the paradigms [56].

Taken together, these results support the use of reach to grasp protocol employing simple actions to use, and minimally invasive sensorimotor paradigm for apathy assessment in people with MND. Specifically, employing the Sensory-Motor Rhythmicity (SMR) parameters linked to the amplitude of the movement and the smoothness of the movement, are particularly relevant to detect the presence of action kinematic modulation in the individual and social conditions in the reach-to-grasp phase. In addition to the assessment of other symptoms such as verbalizations, reduced social initiation, and beyond, the reduction in kinematic modulation may thus contribute to refining social apathy assessment.

There is evidence that age-related changes in reach-to-grasp action kinematics may be affected. However, as participants in the HC, NA-MND and A-MND groups were balanced in terms of demographic characteristics (age, sex, and education), age-related changes cannot be completely explained. Future studies on changes in motor planning and execution in groups such as NA-MND and A-MND participants may reveal similar impairment in global cognitive and motor functions.

and more important is the small sample. It is possible that, for instance, including a bigger number of apathetic participants, more differences between the individual and the social conditions would have been found. Furthermore, a bigger sample would have allowed analyzing correlations between apathy scales and kinematic parameters, and to analyze simultaneously intra-group and inter-group effects, as well as their interactions, thus allowing to significantly reduce Type I errors. Future studies could use the present results to estimate the expected effect size and compute a power analysis to estimate the optimal sample size. Second, the wearable sensor we employed (SensRing), positioned on the index finger, allowed us to collect only data concerning angular acceleration and velocity of the hand. However, it did not allow to collect precise data on the finger movements (such as the amplitude of the maximum grip aperture), and spatial trajectories (such as the maximum height of the wrist trajectory from the working surface, or the length of the wrist pathway), that were found to be sensitive to social intentions in previous studies [43, 48, 64]. Future studies should investigate the interest of combining SensRing with other non-invasive sensors, such as RGBD cameras, to integrate position related data in the analyses. Third, despite trying to make the individual and the social conditions as similar as possible, they slightly differed concerning the precision required for the object positioning (in the cup versus the hand). In the next studies, it would be important to make the two conditions even more comparable, for instance by employing a larger concave base (replacing cup) and a lighter object that can be put on the hand palm without falling. Finally, precisely assessing participants' baseline motor ability may help to disentangle the effects of apathy from basic motor skills, and to explore their relationships. Indeed, even if participants with

future studies with bigger sample sizes, it would be interesting to analyze simultaneously the three apathy dimensions, to understand the role of the social, cognitive/behavioral, and action dimensions in action kinematics. Furthermore, in ND, apathy can be associated with other neuropsychiatric symptoms such as depression, anhedonia, and fatigue [6]. Therefore, it would be interesting to investigate the relationship between all these symptoms and motor behavior. Finally, kinematics in a reach-to-grasp preparation. Previous findings suggest that social apathy relates to the probability to engage in social behavior, with individuals less likely to be being more prone to make efforts [27, 66]. It would be interesting to investigate whether reduced social apathy and action kinematics are related to prosocial behaviors in people with apathy, by employing effort-based tasks [27]. It would be interesting to create more contexts in which action kinematics can be measured by other non-invasive objective measures such as estimated voice analysis during verbal interaction to capture different, complementary aspects of apathy.

CONCLUSIONS

When reaching an object to perform a social action (passing) versus a non-social action (placing), healthy subjects, including children, modulate action kinematics to achieve the goal of the action sequence: despite the object grasped is exactly the same and in the same location, social versus individual goals trigger different movement patterns already in

73], difficulties in motor planning and control, resulting in impairments in action chains (observable, for instance, in reach-to-grasp sequences [74]) may contribute to explain deficits in interpersonal synchrony and intention understanding [75, 76], thus playing a role in explaining autism abnormalities in social interactions. Whether the link between social action modulation and social apathy is bidirectional or not, if the results of the present study are confirmed in a bigger sample, action kinematic modulation may be a non-invasive, simple and fast way to complement the classical clinical assessment with quantifiable and objective data.

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