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Debates

# Toward a motor signature in autism: Studies from human-machine interaction

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ABSTRACT

*Background.* – Autism spectrum disorder (ASD) is a heterogeneous group of neurodevelopmental disorders which core symptoms are impairments in socio-communication and repetitive symptoms and stereotypies. Although not cardinal symptoms per se, motor impairments are fundamental aspects of ASD. These impairments are associated with postural and motor control disabilities that we investigated using computational modeling and developmental robotics through human-machine interaction paradigms.

*Method.* – First, in a set of studies involving a human–robot posture imitation, we explored the impact of 3 different groups of partners (including a group of children with ASD) on robot learning by imitation. Second, using an ecological task, i.e. a real-time motor imitation with a tightrope walker (TW) avatar, we investigated interpersonal synchronization, motor coordination and motor control during the task in children with ASD ($n = 29$), TD children ($n = 39$) and children with developmental coordination disorder ($n = 17$, DCD).

*Results.* – From the human–robot experiments, we evidenced that motor signature at both groups' and individuals' levels had a key influence on imitation learning, posture recognition and identity recognition. From the more dynamic motor imitation paradigm with a TW avatar, we found that interpersonal synchronization, motor coordination and motor control were more impaired in children with ASD compared to both TD children and children with DCD. Taken together these results confirm the motor peculiarities of children with ASD despite imitation tasks were adequately performed.

*Discussion.* – Studies from human-machine interaction support the idea of a behavioral signature in children with ASD. However, several issues need to be addressed. Is this behavioral signature motoric in essence? Is it possible to ascertain that these peculiarities occur during all motor tasks (e.g. posture, voluntary movement)? Could this motor signature be considered as specific to autism, notably in comparison to DCD that also display poor motor coordination skills? We suggest that more work comparing the two conditions should be implemented, including analysis of kinematics and movement smoothness with sufficient measurement quality to allow spectral analysis.



## 1. Introduction

Autism spectrum disorders (ASD) is a neurodevelopmental syndrome staring before age 3 years. Core symptoms include deficit in social interaction and restricted pattern of interests and stereotypies. Motor dysfunction is not included in the cardinal symptoms of ASD [1]. However, patients with ASD have sensorimotor disorders [2–4], impaired performance in skilled motor tasks and gestures [5–7] and difficulties with imitation [8,9], impairments in motor control [10], and difficulties in motor synchronization [11,12]. These disorders in movement are also associated with postural control disabilities [4,13]. Children with ASD exhibit impaired postural control and meaningful variability in posture [14–25].

In typical developing (TD) children, motor control starts at birth. Infants develop skills through a coupling between their sensory and motor systems. They use sensory information to modify

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motor behaviors and learn from their experiences [26]. An essential property of movement is its inherent variability. The stochastic patterns of minute fluctuations in motor trajectories, named submovements [27] or motor noise [28], contribute to the development of motor control [29]. Development of motor control requires forming an internal model of action that accurately predicts the sensory consequences of motor commands [30]. Internal models of motor control are neural representations of the external world used to predict and adjust movements [31,32], allowing coordination with an interaction partner and a fine exploration of the environment. Formation of internal models of action which are critical to the development of social, communicative, and motor coordination behaviors, rely on the coupling between action (motor commands) and perception (sensory feedback) which includes proprioceptive sensory information of kinesthetic order [33].

Torres et al. [28] showed disrupted patterns of proprioceptive sensory feedback in ASD using a pointing motor task and computational analysis of movement kinematics. They found a disruption in the maturation of proprioception, accompanied by behavioral variability in motor control. Across development, they found the persistence of micro-movements in adolescents and young adults with ASD that were underlined by a random (unpredictable) and noisy proprioceptive input. Besides this unique study exploring the role of proprioception and motor control in ASD, a striking observation is the relative high frequency of Ehlers–Danlos syndrome (EDS) in autism [34]. Proprioceptive impairment is one of the core characteristics of EDS [35,36], a group of genetic connective tissue disorders. However, the association between autism, proprioceptive impairments and the maintenance of micro-movements across development remains to be explored.

## 2. Objectives

In the present paper, we focus on the exploration of the motor dimension in patients with ASD through human-machine interaction and summarize a set of studies that we performed to explore human-machine motor imitation. We use computational modeling and developmental robotics involving human-machine interaction, through several paradigms, according to the idea that the structure of social interaction at both behavioral and neural levels is modified by individuals' social/motor traits [37,38]. First, we describe 3 studies that explored the impact of 3 different groups of partners (including a group of children with ASD) on robot learning by imitation. We evidenced that motor signature at both groups' and individuals' levels had a key influence on imitation learning, posture and identity recognition. Taken together these studies confirmed the motor peculiarities of children with ASD despite imitation tasks were adequately performed. Second, we summarize another study using a more dynamic motor imitation paradigm with a tightrope walker (TW) avatar. In this study, we find that interpersonal synchronization, motor coordination and motor control were more impaired in children with ASD compared to both TD children and children with Developmental Coordination Disorder (DCD), meaning that there may be a specific motor signature in ASD.

## 3. Human–robot posture imitation studies from a robot-learning-centered perspective

In this set of studies, imitation is defined as the process by which an individual learns behavioral characteristics from a teacher (i.e., an interactive partner or model). These experiments involve a human–robot learning paradigm. Based on a sensorimotor architecture using artificial neural networks (NN) that enables learning by imitation, identity recognition and posture recognition, Nao is a "naive" robotic system that uses perceptual-motor coupling of what it does to what it sees. Involved in an imitation game with participants asked to imitate 5 different postures (Fig. 1), Nao was used as a tool for clinical evaluation of interaction abilities of children, allowing the extraction of social movement signatures. The robot learning was evaluated with 3 different groups of participants: adults, TD children, and children with ASD. A "social signature" was generated for each participant based on the number of neurons required by the robot to learn by imitation.

The architecture used in these experiments is summarized in Fig. 2A. The neural networks architecture that allows learning by imitation is composed of a Visual Feature NN (VF-NN), a Robot Internal State NN (RIS-NN), an Internal State Prediction NN (ISP-NN) that coupled what the robot sees with what it does, a Short Term Memory NN (STM-NN). To assess posture recognition (PR-NN), we added a dedicated NN. In addition, based on a first exploratory study where we showed that the number of neurons needed to learn in the VF-NN was a good metric of learning complexity and variability of posture imitation of the partners [39], we coupled the VF-NN with a novelty detector (ND, a self-evaluation mechanism that allows Nao to recognize a new partner i.e., to detect novelty in the visual sensations) allowing the robot to achieve the recognition of participant identity in the Identity Recognition NN (IR-NN). This coupling of the number of neuron needed to

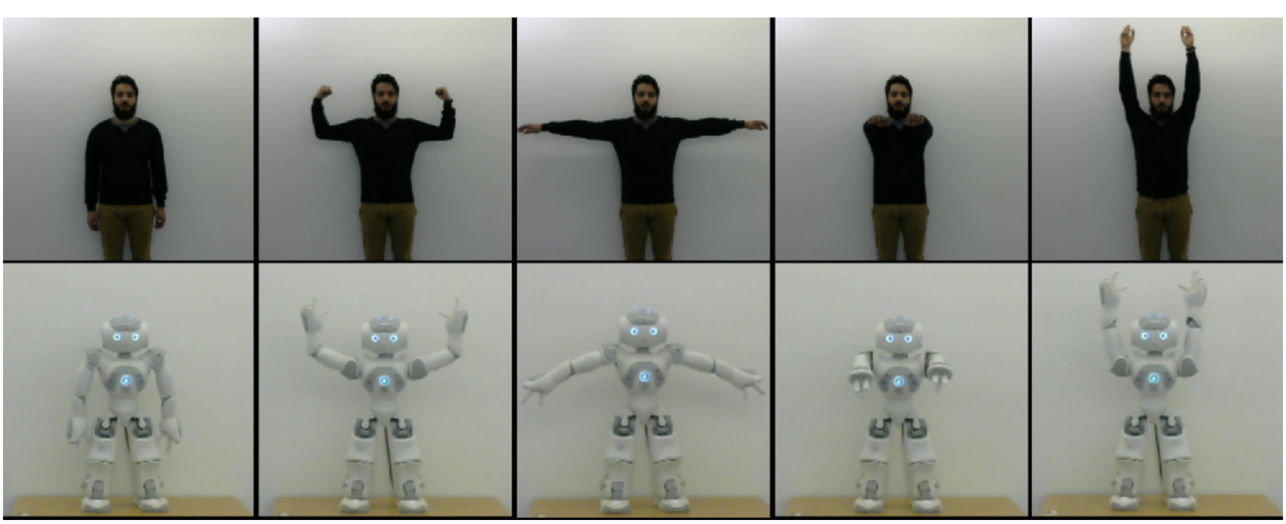

**Fig. 1.** The robot and the human participant producing the five postures during the imitation task.

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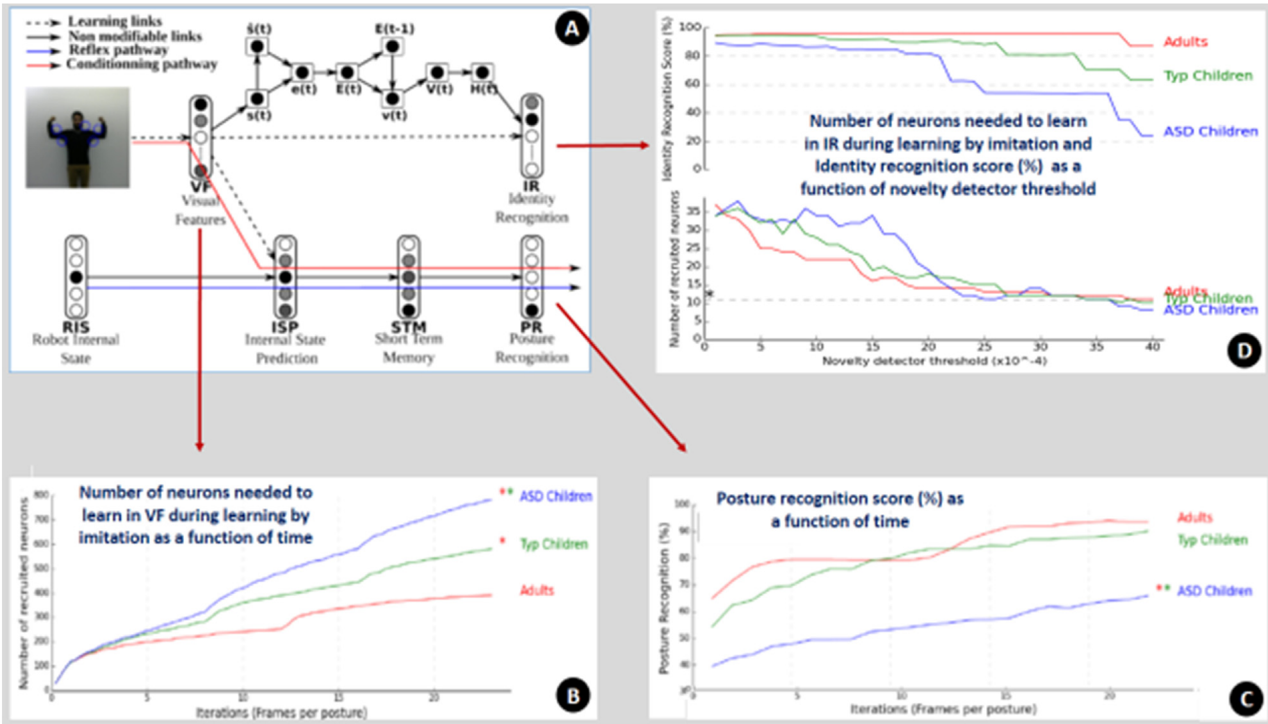


**Fig. 2.** Summary of the experiments using imtation learnin with Nao robot. A. Neural net architecture. B. Number of neurons needed to learn in VF during learning by imitation as a function of time. C. Posture recognition score (%) as a function of time. D. Number of neurons needed to learn in IR during learning by imitation (down) and identity recognition score (%) (down) as a function of novelty detector threshold. Red: adults; green: typical developing children; red: children with ASD; RIS: robot internal state; VF: visual feature; ISP: internal state prediction; STM: short term memory; PR: posture recognition; IR: identity recognition.

learn in the VF-NN and the ND allowed the robot to recognize the participants after the learning phase, above chance levels when presented through a picture [40]. In summary, inspired by the function of social identity carried by imitation [41,42], they explored whether imitation learning during robot-human interaction allows the development of the robot's ability to recognize a human partner that is reencountered at a subsequent time. After a period of mutual imitation with the human partner, the robot was able to integrate the social signatures of actions (postures or facial expressions when they changed the robotic platform from Nao to Kismet) of the participants, and spontaneously develop the ability to recognize them. Finally, we also showed that posture recognition was achievable using a similar testing that the one used for identity recognition and that posture recognition was lower in children with ASD [43]. In Fig. 2B–D, we further explored how learning was modulated by the number of neurons available for the system (an estimation of the cognitive complexity of learning), by time and by the novelty detector threshold.

When we modified off-line the learning-time (from two seconds to 50 seconds), and evaluated posture recognition score for each partner and for each group we found that the robot learned by imitation more easily with adults compare to both children groups, thus indicating a developmental age effect. Additionally, the robot has more difficulties (i.e., more neurons are recruited in VF-NN) during learning by imitation with children with ASD (Fig. 2B). This is likely due to their highly variable movements.

Similarly, when we modified off-line the learning-time and explored posture recognition score for each partner and for each group we found that, for each participant, the longer was the interaction the better was his/her posture recognition score. This result was also found in the group analysis. Furthermore, in terms of posture recognition scores, unlike for TD group for which the increase of recruited neurons compensates the difference with adults, for children with ASD posture recognition scores remained significantly lower than that of the two other groups (Fig. 2C).

Finally, in the first study, the number of neurons needed to learn recognition in IR-NN was fixed to one per participant and the novelty detector threshold was also fixed [40]. In a last exploration, we studied how changes in parameters influenced robot's learning [43]. In Fig. 2D, we simulated a variation of the threshold parameter controlling the novelty detection sensitivity. The partners' identities in each group were learned sequentially. To ease the comparison, we kept the same amount of subjects ($n = 11$) in each group and randomly discarded 4 TD children and 4 children with ASD. We show the effect on identity recognition scores (2D-top) and on the number of neurons recruited (2D-down) for the 3 groups. At any tested threshold, identity recognition scores of adult partners were higher compared to those of TD children, which were higher to the recognition scores of children with ASD. Considering the recruitments of neurons in IR-NN, we found that (i) the threshold needed to perform best identity recognition for both children groups was below than the threshold for adults, respectively (Fig. 2D-top); and (ii) for almost all the tried threshold intervals, the system recruited more neurons while learning from children with ASD compared to TD children and from TD children compared to adults (Fig. 2D-down). To achieve the identity recognition task and reach score higher than 85%, the architecture needed 12 neurons for adults, 15 neurons for TD children and more than 30 for children with ASD [43].

All together, these different results show that participants with ASD have a higher variability in terms of posture realization and, for the robot, a higher complexity of the visual input when it is learning by imitation with children with ASD compared to other partners (adults or TD children). This is revealed by the higher number of neurons needed to learn to capture this variability. It seems that the robot is able to detect subtle instabilities in ASD children's posture (i.e., in the spatial and temporal micro-stability) that were

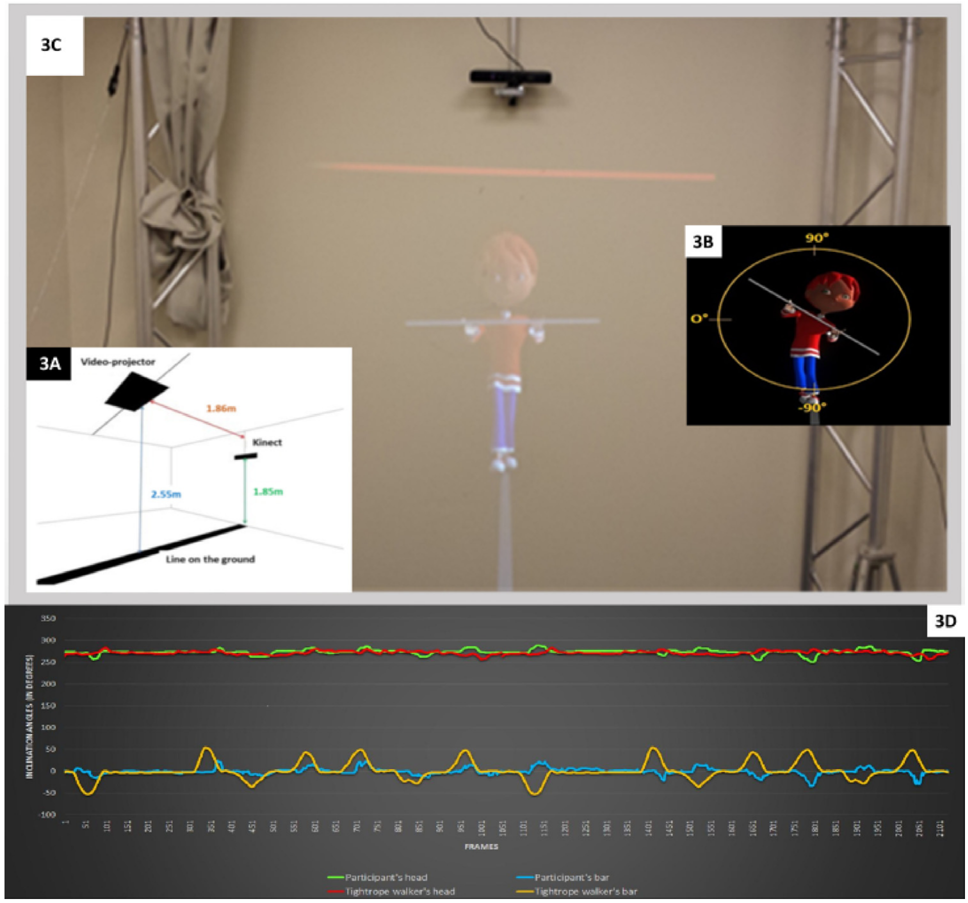


**Fig. 3.** Principles and set-up of the experiment. A. Schematic illustration of the experimental room. B. Tightrope walker's bar inclination measurement. C. The roll angle of the head and of the bar in the frontal plane were recorded (left) projection on the wall of a tightrope walker avatar. D. Registration of participant's and TW avatar's heads and of participant's and TW avatar's bars.

undetected by a therapist in a clinical setting [39]. These results motivate further exploration of ASD motor signature.

## 4. Interpersonal synchronization and motor dynamics during human-avatar motor imitation

Behavioral imitation is common in children with autism spectrum disorder (ASD) despite frequent motor coordination impairments. Impairments in imitation abilities have been also described in other neurodevelopmental disorders such as developmental coordination disorder (DCD). Children with DCD display motor incoordination and visual-spatial processing deficits [44], which may affect their imitation abilities [45,46]. How motricity impacts imitation during long lasting semi-ecological conditions has not been carefully investigated. In Xavier et al. [47] experiment, we explore behavioral imitation abilities in terms of interpersonal synchronization, motor coordination and control by means of an interaction paradigm using a TW avatar. To get a better understanding of imitation difficulties in children with ASD, we explore the potential alteration of the development of behavioral imitation abilities in children with ASD in comparison with DCD children and TD control children. ASD and DCD have in common motor and visual-spatial difficulties. Therefore, comparing these two pathological groups offered the opportunity to disentangle the contribution of visual-spatial and motor coordination impairments in motor imitation difficulties. For this study, we recruited 85 children and adolescents (39 controls with typical development, TD; 29 patients with ASD; 17 patients with DCD), aged 6 to 20 years who participated to a behavioral paradigm. Participants, standing and moving in front of the TW avatar, interacted with it standing and moving as well. During the protocol, we measure automatically and continuously avatar's and participant's heads and bars from RGB sensor recording to assess participants' behavioral imitation (Fig. 3).

In this experiment, we find that interpersonal synchronization (as evidenced by the synchrony between the participant's and the tightrope walker's bars) and motor coordination (as evidenced by the synchrony between the participant's bar and its own head axis) increased with age and were more impaired in patients with ASD compared to both TD children and children with DCD. Also, motor control as evidenced by the movement angle standard deviations of participants' bar and head were significantly larger in ASD compared to both TD children and children with DCD [47].

In sum, behavioral imitation abilities during an ecological interaction with a TW avatar show subtle impairment in children with ASD as compared to TD children or children with DCD, both in terms of interpersonal synchrony, motor coordination and control. These results question how motricity matures in terms of motor control and proprioception in children with ASD. Exploring motor control from a developmental point of view through a dynamic process like imitation poses significant pragmatic challenges for researchers and clinicians alike.

## 5. Discussion

Based on the clinical literature on ASD (see intro) and the set of studies using human-machine interaction that we performed with children with ASD, it appears that the way children with

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autism behave during motor tasks expresses a specific behavioral signature. This signature is evidenced from the robot-learning-centered perspective we used in our developmental robotics studies [39,40,43]. The signature is also captured during the ecological dynamic task with the TW avatar [47]. However, to be specific, this motor signature needs to ascertain three conditions. First, it should be specific in terms of clinical label within the neurodevelopmental disorder group. The fact that children with ASD significantly differ from children with DCD in our tightrope walker ecological paradigm is encouraging.

Second, we need to ascertain whether the so-called behavioral signature found during motor interaction between children with ASD and machine is motor in essence [48]. Indeed, motor activity is a behavioral output that is a cascade of different skills. Development of motor control requires forming an internal model of action relying on the coupling between action (motor commands) and perception (sensory feedback). Critical to the development of social, communicative, and motor coordination behaviors, internal model of action accurately predicts the sensory consequences of motor commands [30]. To disentangle the contribution of motor dysfunction per se in these motor activities, research should focus on specific metrics that may capture both sub-movements and their possible effect on movement smoothness (see below). The jerk and the jerk ratio may be a first approximation [49]. Jerk is the 3rd derivative of shifting. Jerk ratio is the integrated squared jerk of a movement. Comparison between tasks usually requires normalization [49]. Another method may be to define speed profile during the task meaning calculating the duration and number of pics of speed. A common expected result is a positive correlation between the number of pics of speed and duration. Finally, the study of movement phases through spectral analysis. This task is delicate as it may be necessary to distinguish postural oscillation [50].

Third, we also need to ascertain whether this motor signature is found in all or a limited set of motor tasks (e.g. pointing; writing; motor imitating). Back to the studies that have specifically investigated motor characteristics in ASD, we found several studies describing disruption in movement kinematics in ASD during goal directed actions [10,14,21,51–54]. Since motor action needs some kind of continuous control during the execution of a given movement [48,55–60], voluntary movements have discontinuities whose frequency (around 10 Hz) is a fundamental characteristic of motor control. These intermittencies, called sub-movements, are corrections made to counter the effect of initial inaccuracy of movements [61]. During child development, the gradual progression of motor control with higher levels of spatial/temporal movement accuracy results in an increase of its smoothness [62] and a decrease of its jerkiness. This phenomenon includes a reduction in the number of the sub-movements [63–65], which appear higher in peak speed, longer in duration, and more overlapped [66].

Few studies using different motor tasks (pointing, reaching to grasp, reaching and dropping) found atypical sub-movement patterns in children with ASD [28,67,68]. Interpretations are not consensual and authors have proposed several underlying mechanisms: desynchronization of sub-movements within a single action; impairments of motor control; difference in nature regarding sub-movements (called micro-movements); disrupted patterns of proprioceptive sensory feedback [28,69]. However, postural control is integral to the execution of action, serving as a reference frame for the production of accurate, smoothly continuous and sustained movements [70–72]. From the current literature, it remains also difficult to ascertain that the behavioral signature present during movement kinematics is different in nature to the posture variability found in ASD.

As we said previously, besides motor signature per se, it remains difficult to ascertain to what extent some of these motor problems are specific to autism [73], i.e. could constitute a motor signature, notably in comparison to other neurodevelopmental disorders such as developmental coordination disorder (DCD) that also display poor motor coordination and skills [74,75]. Direct comparisons between the two conditions has been limited in the literature. More work should be implemented comparing the two conditions and including motor capture kinematics allowing analysis at a temporal level that addresses movement variation at high frequency range with sufficient measurement quality.

## Disclosure of interest

The authors declare that they have no competing interest.

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