Embodied Simulation Based on Autobiographical Memory

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Abstract. The ability to generate and exploit internal models of the body, the environment, and their interaction is crucial for survival. Referred to as a forward model, this simulation capability plays an important role in motor control. In this context, the motor command is sent to the forward model in parallel with its actual execution. The results of the actual and simulated execution are then compared, and the consequent error signal is used to correct the movement. Here we demonstrate how the iCub robot can (a) accumulate experience in the generation of action within its Autobiographical memory (ABM), (b) consolidate this experience encoded in the ABM memory to populate a semantic memory whose content can then be used to (c) simulate the results of actions. This simulation can be used as a traditional forward model in the control sense, but it can also be used in more extended time as a mental simulation or mental image that can contribute to higher cognitive function such as planning future actions, or even imagining the mental state of another agent. We present the results of the use of such a mental imagery capability in a forward modeling for motor control task, and a classical mentalizing task. Part of the novelty of this research is that the information that is used to allow the simulation of action is purely acquired from experience. In this sense we can say that the simulation capability is embodied in the sensorimotor experience of the iCub robot.

Keywords: Humanoid robot, perception, action, mental simulation, mental imagery, forward model.

1 Introduction

One of the central capabilities that cognitive systems provide to living organisms is the ability to "travel in time," that is, to imagine the future, and recall the past, in order to better anticipate future events [1]. This can be considered in the context that one of the central functions of the brain is to allow prediction [2, 3]. One of the most classical uses of prediction in the context of control is the forward model, which allows a system to predict responses to a motor command, and then compare the predicted and actual outcome. This notion has been extensively applied in the

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N.F. Lepora et al. (Eds.): Living Machines 2013, LNAI 8064, pp. 240–250, 2013.

neuroscience of motor control [4]. At a more extended time scale, a suitably detailed forward model can be used as a simulation system for allowing the system to image how things might have been, or how they might be in the future. This can allow perspective taking, as required for solving tasks in which one must take the perspective of another. In the “Sally – Anne” task, a child is shown a set-up with two dolls, Sally and Anne. Sally puts her ball in a basket, and then leaves. Meanwhile, Anne moves Sally’s ball into a box. Then Sally returns, and we can ask the child “where will Sally look for her ball?” Frith and Frith demonstrated [5] that before a certain age, children will “mistakenly” indicate that Sally will look in the box, the ball’s actual location, rather than in the basket, where she put it. They suggest that the ability to mentalize – to represent other’s mental states – relies on a system that has evolved for representing actions and their consequences. Such a capability to compare representations of others mental states with reality can form the basis for detecting that another agent is not telling the truth [6]. In the current study, we present a capability that allows the development of an internal simulation function, based on experience acquired by the agent, which allows the generation of mental simulations that can be used both in low level motor control.

The Experimental Functional Android Assistant (EFAA) system functions in a domain of physical interaction with a human as illustrated in Figure 1. Objects are manipulated by the robot and the human in cooperative interactions, and thus it is important that the EFAA system can accurately perform these manipulations and keep track of the actual and predicted physical state of itself and the human in their shared space.

2 System Description

The system provides control for real-time human interaction with the iCub robot that is achieved by articulation of three software modules: Autobiographical Memory, abmReasoning and OPCManager. The two first modules (AutobiographicalMemory and abmReasoning) have been previously described [7, 8]. They provide the ability for the system to store the history of all interactions in the ABM, and to extract conceptual information from the ABM, including the meaning of spatial and temporal referencing terms. We will briefly describe these functions, and then focus on the OPCManager (OPCM). Our complete system is developed in the context of the emergence of a self of the robot (use of an autobiographical episodic-like memory and a reasoning based on the experience) but an important property of the self is the ability to mentally simulate and predict consequences of the actions of himself or of other.

Illustrated in Figure 1, the Objects Properties Collector (OPC), contains the world-related knowledge of the robot at the current time. Here, we use two different OPCs. One will be related to the “real” world (realOPC), and the second one to the ”mental” picture of the robot and to his imagination (mentalOPC). The main purpose of the OPCmanager module will be to simulate in the mentalOPC activities previously learned through the joint action of the AutobiographicalMemory and the ambReasoning, then to observe the possible implication of these activities, and to compare this with the final state of the same activities in the real world.

In summary, we will focus on the coordinated interaction of the three modules: 1) Autobiographical Memory: Take a snapshot of the world at a given time, Store snapshots and manage them. 2) abmReasoning: Manipulate the data of the ABM, Summarize and generalize different levels of knowledge. 3) OPC Manager: Simulate action interaction in a mental OPC, and extract differences between realOPC and mentalOPC.

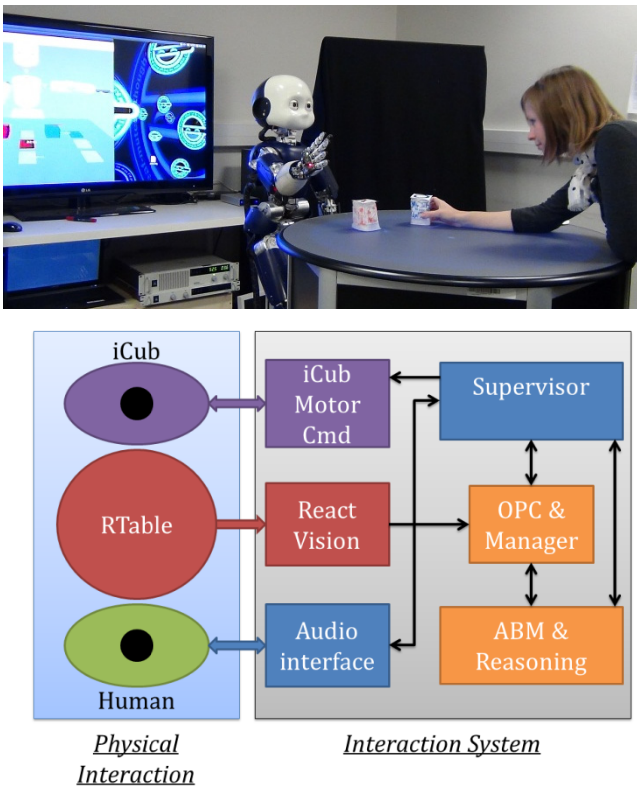

Fig. 1. Illustration of the iCub EFAA interacting with a human (Above), and System Architecture overview (Below). Human and iCub interact face-to-face across the ReacTable, which detects objects through the translucid surface, and communicates object locations via ReactVision to the Object Property Collector (OPC). The Supervisor coordinates spoken language and physical interaction with the iCub via spoken language technology in the Audio interface. The autobiographical memory ABM & reasoning system encodes world states and their transitions due to human and robot action as encoded in the OPC, and generates semantic representations. The OPC manager generates the representations of the actual and imagined states.

2.1 Autobiographical Memory and ABM Reasoning

The Autobiographical memory (ABM) is made up of an episodic memory and a semantic memory. The Episodic memory consists of 12 SQL tables, and stores the content of the OPC, with related contextual knowledge. The information will be: content of the realOPC, time, date, agent performing an action, semantic role of the argument of an action (i.e.: "ball": object, "north": spatial).

The Semantic Memory is made up of 12 SQL tables and stores the knowledge of the iCub related to different levels. Levels are: spatial, temporal, contextual, shared plan, behaviors. The semantic memory is constructed by extracting regularities from the episodic memory as human and robot actions cause changes to the states of objects on the ReacTable.

As such actions take place during the course of ongoing interactions, these events are stored in the episodic memory. The ABMreasoning function then extracts regularities that are common to experiences that are encoded in the episodic memory, to populate the semantic memory. The semantic memory thus includes the names and locations corresponding to locations taught by the human, and actions (e.g. *put* an *object* at a *location*) and their pre-conditions (e.g. that the object should be present) and post-conditions (e.g. that the *object* is now at *location*). Thus, through interaction, the system learns about the pre- and post-conditions of actions. This knowledge will be crucial in allowing the system to mentally simulate action.

2.2 OPC Management of Physical Reality and Mental Simulations

The OPC manager ensures the proper functioning of the realOPC and the mental OPC. The realOPC should maintain an accurate reflection of the physical state of the world. This state will be modified after the execution of actions. Thus, when the robot or the human perform an action of the type “put the triangle on the left”, the physical state changes that result from this will be that the triangle is at the north location. For the realOPC, these changes will occur as part of the normal functioning of the OPC as it is updated by perceptual inputs from the ReacTable. This corresponds to the update of an internal model (the realOPC) via perception (ReactVision inputs to realOPC).

The novel aspect concerns the updating and maintenance of the mentalOPC. The function simulateActivity will simulate an action by retrieving its pre-conditions and post-conditions from the Semantic memory, and then “executing” this action by checking that its pre-condtions hold in the mentalOPC, and then updating the mentalOPC so that the post-condtions now hold, and the pre-conditions are removed. Thus, we emphasize that mental simulation is based on experience, initially encoded in the episodic memory and then extracted in the semantic memory.

3 Experiments

Here we report on two experimental evaluations of the use of the real and mental OPCs in different contexts.

3.1 Forward Model in Grasp Control

A current problem in robotics is the use of feedback in motor control, for example, when a robot attempts to grasp an object and the grasp fails, feedback can be used to detect the failure [9]. Such a feedback control look is illustrated in Figure 3. The motor command is sent to the forward model, and to the body, and the resulting predicted sensory feedback and actual sensory feedback are compared. If they match, the movement has been successfully completed, and if not, a failure is detected. We can use this method in the dispositive described above with the iCub. After experience producing the "put object at location" action, the system has acquired semantic information that the result of this action is that the object is now positioned at the specified location.

Functionally, the mentalOPC is used as the forward model. The "put" command is sent for execution to the ICubMotorCmd module, and it is also sent for simulation to the SimulatActivity function of the OPCmanager. The realOPC and mentalOPC can then be compared to assess the success of the action.

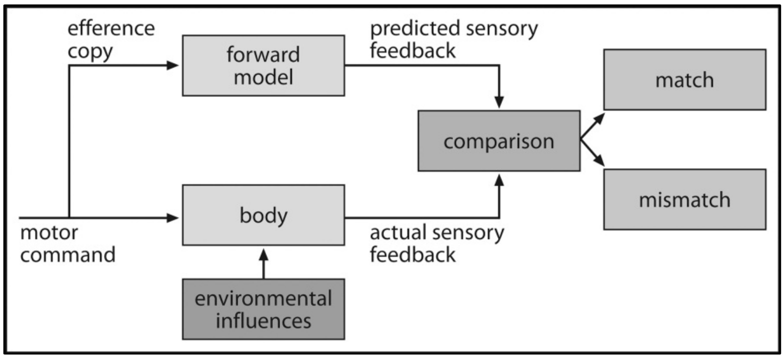

Fig. 2. Illustration of the forward model in the context of motor control. The motor command is sent to the motor command system and to the internal model. Subsequent comparison allows the system to determine if the grasp was correctly executed. Figure from [2].

Figure 4 illustrates the contents of the realOPC and mentalOPC before and after a successful "put circle left" action is executed by the iCub. The circle is indicated in the OPCs by a blue cube. In the Before panels it is at the "North" location near the robot's midline, and in the After panels it is displaced to the robot's left, to the location labeled Left. The diffOPC function produces a report indicating that there is no significant difference in the two positions, as illustrated in Table 1.

Figure 5 illustrates the mentalOPC and realOPC before and after "put cross left" action in which there is a physical disturbance during the execution by the iCub. In the lower right panel (Actual – After) we can observe that the representation of the cross object is not positioned on the localization "Left" in contrast to the predicted location that can be visualized in the upper right panel (Mental – After). During the execution a perturbation occurred and the put action resulted in a final positioning of the object that does not match with the predicted location. This mismatch is detected by the diffOPC function, as illustrated in Table 2.

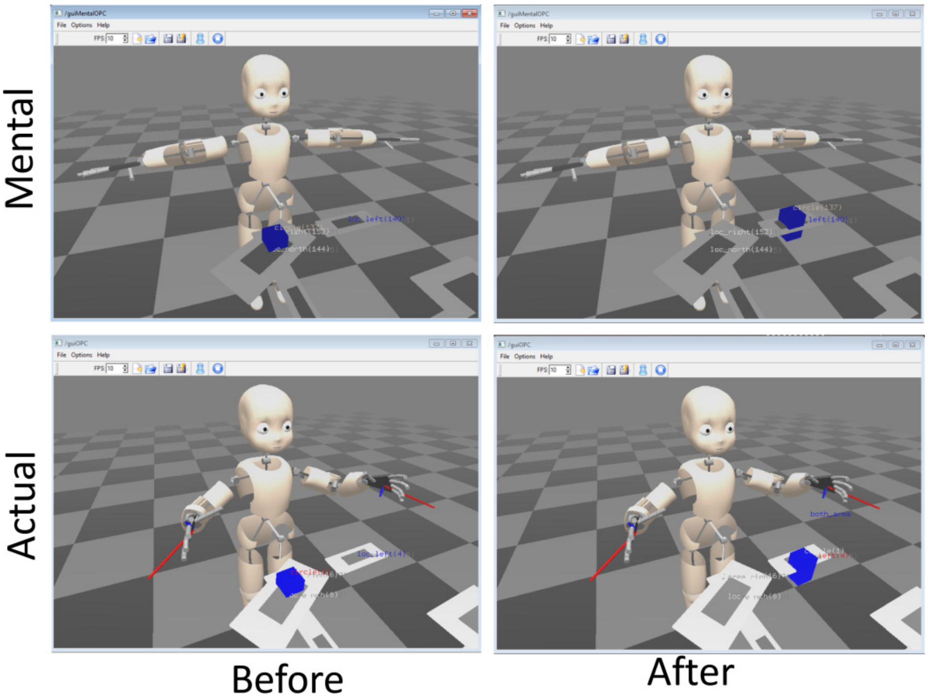

Fig. 3. Mental image and actual physical state before and after a successful grasp and move action. The action to perform is to put the circle (the blue object) to the left of the robot in the delimited location..

Table 1. Comparison from diffOPC function of realOPC and mentalOPC indicating no difference.

```
:ircle
bot_position_x -0.025075
bot_position_y 0.016605
bot_orientation_z -0.048426
_position_x 0.112762
_position_y 0.180602

 semantic differences
```

The detected mismatch can be used to allow the iCub EFAA to determine a correcive course of action. Our next step in this context will be to include experiments with this forward modeling capability integrated in the iCubMotorCMD so that failed actions can automatically initiate appropriate retrials.

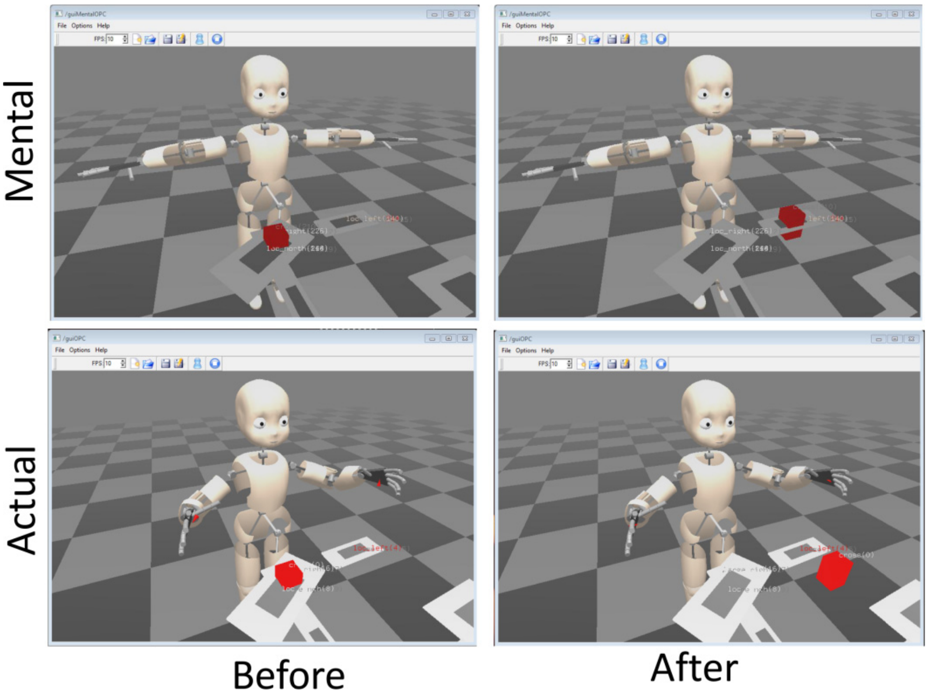

Fig. 4. Mental image and actual physical state before and after an unsuccessful grasp and move action. The final state of the object in the actual condition is different from that in the mental simulation (forward model), thus indicating that the action failed. The action to perform is to put the cross (the red object) to the left of the robot in the delimited location.

3.2 Simulating Other's Beliefs in the "Sally Anne" Task

Such mental simulation can also contribute to the ability of the robot to mentalize. Mentalizing is the ability to represent the mental states of others, traditionally referred to in the context of theory of mind (ToM) tasks [5]. A classic method to assay this capability to represent false beliefs is via the "Sally – Anne" task. In this task, the

Table 2. Results returned from diffOPC comparing realOPC and mentalOPC. The comparison indicates a significant difference, corresponding to the error in the execution of the action.

```
Entity : cross
        robot_position_x -0.091195
        robot_position_y -0.035511
        robot_orientation_z 0.179689
        rt_position_x 0.194235
        rt_position_y 0.183612

Semantical differences :

Entity : icub
        Beliefs removed:cross is left (mental-predicted)
```

child is shown a small stage with two dolls, Sally and Anne, and a toy ball. Sally puts her ball in a basket, and then leaves. Meanwhile, Anne moves Sally's ball into a box. Then Sally returns, and we can ask the child "where will Sally look for her ball?"

A long history of experimental research has demonstrated that the ability to perform tasks that require such representations develops over time, though the details of precisely when young children can perform such tasks depends signficicantly on the detail of how the task protocol is implemented, and children as young as 15 months of age can be demonstrated to represent the false beliefs of others [10].

We hypothesized that the mentalOPC can allow the iCub EFAA to resolve this problem correctly. The mentalOPC can be used to represent the intial state of affairs. The key element is that after Sally leaves, whatever happens in the mentalOPC - which is intended to represent Sally's perspective - should not change and should not be subject to the results of any actions that Sally does not actually witness.

The contents of the realOPC and mentalOPC in this context are represented in Figure 6. In this case, while the agent Sally is present, the toy is placed on the left. This is represented in the mentalOPC and the realOPC. In the After column, for the

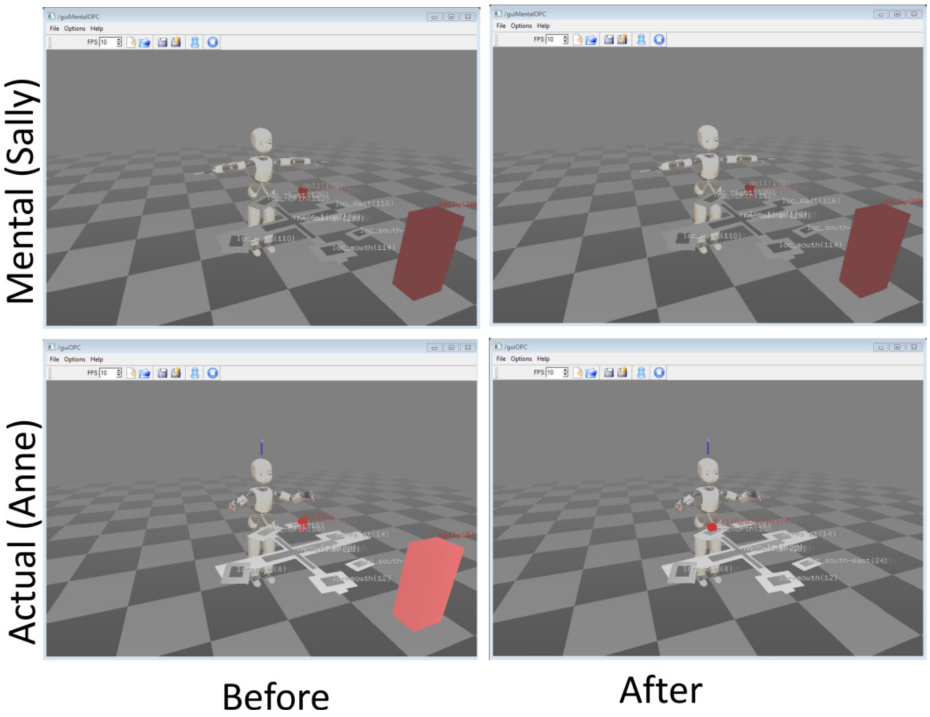

Fig. 5. Contents of mentalOPC and realOPC in the Sally-Anne task. In the "Before" column is represented the contents of both OPC when the toy has been placed at the first location. The mentalOPC is the systems representation of what it and Sally have seen. In the "After" column, the Actual situation represents the contents of the realOPC after the toy has been moved. In that same column the mentalOPC represents the what Sally observed before she left. If this is maintained in memory, then it will persist after the world has been changed, and it can be used to mentalize about where Sally would look for the toy.

Table 3. Results returned from diffOPC comparing realOPC and mentalOPC. The comparison indicates a significant difference, corresponding to difference between the “false belief” attributed to Sally in the mentalOPC and the “true beliefs” attributed to Anne in the realOPC.

```
3 entities changed :
Entity : toy
        robot_position_x -0.034557
        robot_position_y 0.276599
        robot_orientation_z -0.042716
        rt_position_x -0.118581
        rt_position_y -0.252269
Entity : icub
        Beliefs added :toy is column toy is north (after)
        Beliefs removed :toy is left, Sally is isPresent (before)
Entity : Sally
The beliefs of Sally didn't change, because she wasn't here.
Her beliefs are : toy is left.
```

realOPC we see that Sally is no longer present, and the object has been moved to the North location. The mentalOPC is the same image as seen when Sally was present, and it is not updated. The ability to maintain this representation allows the system to recognize the mismatch between what Sally saw, and the actual state of the world.

Here we see that the use of the mentalOPC allows the system to “mentalize” about the belief state of another agent. This experiment has potential impact in the context of the ongoing debate on what is required for passing false belief tasks, and will be addressed in the discussion.

4 Discussion

The human cognitive system allows us to travel in time and space – we can imagine possible futures, and relive and analyze the past [1]. To do so, the system requires the ability to simulate itself and its activity in the world. We hypothesize that this simulation capability derives from the long evolved capability for forward modeling that was crucial for the ability of advanced primates to navigate through a complex world where real-time sensorimotor was crucial to survival. In the current research we demonstrate a developmental mechanism that could contribute to the emergence of such a simulation capability.

Through the accumulation of its own experience, the iCub EFAA can extract the regularities that define the pre- and post-conditions of its physical actions, and those of the human. This knowledge is then used to drive the mental simulation of action, which can actually operate faster than real-time, and generate predictions of expected outcome before the real movement is achieved. We demonstrate the functionality of this mechanism in two settings: Forward modeling in sensory-motor control, mentalizing in a false-belief task.

Learning forward models has been successfully applied in robotics [11, 12]. In the context of forward modeling, it is important for the system to detect that inconsistent information is being provided. This can be important in the ongoing learning of the system based on experience. Thus, if the human says that it will perform an action, and then the system can detect a difference between the actual and predicted action, then it can mark this experience as suspect, and not include it in future learning, thus not contaminating experience with questionable content.

In the context of mentalizing and the false belief task, the current research has significant potential impact. There is an ongoing debate concerning the nature of the mental processes that are required to take the mental perspective of another agent. This includes discussion of whether distinct language capabilities are required [10]. Our research provides insight into this question, by illustrating how a simulation capability that is directly derived from experience can be used to provide an agent with the basic representational capabilities to perform the false belief task.

It can be considered that the mere notion of "autobiographical memory" presupposes that the system must have a first person perspective, from which that memory is situated. The notion of first person perspective is in fact a deep philosophical issue (see eg. [13]). From the perspective of the current research, we can say that the robot has taken steps towards achieving a minimal form of 1PP in that it has developed an integrated representation of itself within the peripersonal space. This is also related to the notion of ecological self as defined by Neisser, which is the individual situated in and acting on the immediate environment [14]. What is currently missing with respect to these notions of self is a reflective capability, where the system reasons on a self-model as an integrated model of the very representational system, which is currently activating it within itself, as a whole [15].

In summary, the current research makes a significant contribution to the cognitive systems research. It allows the iCub EFAA system to autonomously generate an internal simulation capability based on its own personal experience. This simulation capability can operate at the level of physical control, and at high levels of cognition including mentalizing about the belief states of others. Our current research integrates this capability in the context of simulated situations models and language comprehension [16, 17].

Acknowledgements. This research has been funded by the European Commission under grant EFAA (ICT-270490).

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