

The role of sensorimotor experience and embodiment in education: evidence from neuroscience and a historical perspective

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Abstract How can neuroscience help improving pedagogical theories and practices? In the following, after discussing the contemporary interdisciplinary context for the interaction between neuroscience and pedagogy, we will review key neuroscientific developments about the role of the sensorimotor system and its involvement in cognitive functions (embodiment), highlighting how they are relevant to pedagogy. Language, especially as understood according to the embodied perspective in its connections with concrete sensory, motor and emotional experiences, turns out to be a key pedagogical tool. Finally, the theories and approaches of pedagogists J. Dewey, M. Montessori, L. Vygostkij, and P. Freire will be briefly presented. This will show how classical pedagogy indeed anticipated, on an experiential and observative basis, the notion that higher cognitive functions are grounded in sensorimotor experience. This review shows how the embodied approach to cognition and language and the knowledge of the detailed neurophysiological mechanisms underlying skill and motor learning, social interactions and language ground, support and expand classical approaches in pedagogy, providing them with a strong scientific background. In the future, this expanding knowledge should affect educational practice by refining learning strategies and providing new learning tools, and by supporting teaching methods with a solid scientific basis.

Keywords: educational neuroscience, sensorimotor system, embodied cognition, embodied language, learning and teaching

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0. Introduction¹

Education has always been a strategic field in all societies, even more so today. The knowledge to be mastered by any member of our societies is wide and sophisticated, often not entirely transparent, or easy to grasp. Every human being learns constantly, lifelong. This makes pedagogy, the science of education principles, methods, and aims, all the more relevant.

Pedagogy has a long tradition. Neuroscience is newcomer in the education field. How can neuroscience be helpful in making pedagogical theories better grounded and pedagogical practices more effective? Since pedagogy aims at improving the teaching practices, pursuing this goal also requires knowledge of how the learners learn, of their potentialities and needs, and of the neural structures supporting the learning processes. It is precisely here that neuroscience comes in as a valuable partner of pedagogy. Nowadays, much of learning and teaching is fundamentally mediated by language, and oftentimes concerns linguistic practices as such. Also from this viewpoint, neuroscience seems to be key to understand how language works and how pedagogical strategies may maximize language effectiveness in teaching and learning contexts.

In the following, we will discuss four main points: 1. The contemporary context in which the interaction between neuroscience and pedagogy can develop, stressing some fundamental aspects of any educational practice and hence the core of pedagogy. 2. The recent developments in neuroscience research that might spur advancements in pedagogy; in particular, we will focus on the cognitive role of the brain sensorimotor system and on the approach of embodied cognition and language, reviewing the key findings and theories in the field, and how they are relevant to pedagogy. 3. Recent developments in pedagogical research that take into account insights from basic neuroscience and from movement science to the aim of developing concrete educational strategies. 4. Finally, we will show interesting convergences between the reviewed neuroscientific developments and classical pedagogical theories.

1. A contemporary framework for pedagogy as a science

1.1. Why teaching is necessary

Learning is common to most animal species (e.g., Whiten et al. 2016; Whiten 2021) as significant information is transmitted from generation to generation not just via genetic inheritance but also directly passing behavioural patterns (Jablonka and Lamb 2014). This is particularly evident in humans, where the information and knowledge to be transmitted from generation to generation has become increasingly complex. This makes teaching so fundamental in our society and implies that teachers acquire specific skills and attitudes to ensure transmission. Indeed, there are different situations where learning needs to be supported by teaching. This may happen when copying others' behaviour does not ensure transmission because (Kline 2015): (1) the learner lacks the basic knowledge or skills to engage in the learning situation; (2) the learner cannot undertake the task as it is too difficult or dangerous; (3) the learner does not pay attention to the relevant stimuli; (4) the learner does not notice the consequences of its behaviour; (5) the learning situation is opaque, so that the learner cannot discern relevant stimuli, or lacks basic knowledge to manage the stimuli and/or the task. In all these situations, learning requires an active engagement of the expert individual. Such active engagement consists primarily in a modification of the behaviour that the expert acts to facilitate the learning process to the advantage of the learner. This captures teaching *core* feature.

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Michelle A. Kline (2015) distinguishes five teaching forms, each one able to solve one of the above-listed reasons why learning does not ensure transmission.

- A. *Teaching by social tolerance*: the expert individual does not stop the naïve one to participate in an activity, even if this hinders the proper execution of the activity itself.
- B. *Teaching by opportunity provisioning*: the expert individual creates specific opportunities and facilitated contexts for the naïve one to learn by his/her own.
- C. *Teaching by stimulus or local enhancement*: the expert individual acts in ways that prompt the naïve one to focus his/her attention on the relevant stimuli.
- D. *Teaching by evaluative feedback*: the expert individual explicitly emphasizes and assesses the consequences of the learner's behaviour.
- E. *Direct active teaching*: the expert individual's behaviour is organized so to make relevant information manifest to the naïve one and perceived as novel knowledge content. This advanced form of teaching implies a knowledge background shared by expert and naïve individuals, as well as affective means of direct communication. Formal teaching at school is a case in point.

Thus, teaching can be fundamentally understood as the attitude to modify one's own behaviour in view of facilitating learning by others. There are three characteristics of teaching that are most relevant for what follows. First, teaching requires an effort on the side of the teacher (the expert individual) to "resonate with" the learner, to enter in an empathic relation with him/her. Indeed, the learner must engage in social interactions with the teacher independently of immediate payoff, this being promoted by empathic relations between teacher and learner. This appears as a crucial pre-condition for the teacher to share experiences and to improve the experiential (sensory, motor and emotional) competence of the learner. Importantly, as it will become clear in the next section, current neuroscience emphasizes how the physiology and "working" of the human brain is specifically tuned to such a task. Indeed, both basic and sophisticated mechanisms are active in the human brain to ensure mutual inter-subjective and social understanding even earlier than explicit exchanges vehiculated by overt communication or language occur. Second, teaching has primarily to do with supporting the learner in *perceiving* relevant aspects of the environment and in *performing* effective and functionally directed actions. This justifies the emphasis on sensorimotor experience we will discuss in the next section. Third, successful teaching should induce the learners *to build upon the capacities they already possess in their sensorimotor "repertoire"*.

It is worth stressing that learning and teaching are relevant not only to favour the acquisition of specific notions but may contribute to improve life conditions and explore novel lifestyles (Colagè and d'Errico 2020). Moreover, teaching «allows for the acquisition of knowledge contents that are not only functionally non-transparent, but that do not seem to (or actually do not) have any direct and perceivable adaptive value at all» (Csibra and Gergely 2006: 254). Transmission of knowledge certainly increases effectiveness in modifying the environment to make it more hospitable, and, in turn, these improvements of the environment may contribute to facilitate the transmission of knowledge and its application to novel situations (Buffon and Colagè 2022). For example, we have learnt to build houses, schools and hospitals, but these are also the places where we can live more comfortably, we can learn more easily or we can apply scientific knowledge to improve health.

1.2. The relevance of language in pedagogy

Despite learning and teaching do not strictly need language, they are enormously potentiated by linguistic communication. There are several theories in different disciplines about the origin and evolution of language. Although an extensive review of such theories exceeds the scope of this paper, it is worth mentioning a few approaches.

A first class of approaches emphasizes the linkage of the emergence of human language with tool-use and tool-making. In this respect, language may have unveiled opaque information for production and use of functional tools. There is indeed experimental evidence that teaching assisted by *verbal linguistic* communication significantly improves transmission of Palaeolithic technology (Morgan et al. 2015; see also Stout and Chaminade 2012). A recent study shows that complexification of culture in the Palaeolithic was accompanied by transmission strategies increasingly requiring overt, linguistic explanation (Colagè and d’Errico 2025).

A different but related development is Michael Arbib’s “mirror system hypothesis” (Arbib 2005, 2012) that stems from an early understanding of actions as relevant in communication (Rizzolatti and Arbib 1998). Since the sensorimotor system is endowed with a fundamental mechanism (the mirror mechanism, discussed below) allowing a matching between one’s own motor representations and observed actions done by others, the sensorimotor system creates a link between an agent and an observer that also grounds the link between a sender and a receiver in communicative processes. On this basis, according to this hypothesis, the latest stages of language evolution might have been driven by the need for precision in the transferred information, which prompted language to develop up to its current sophistication (Arbib 2012).

These approaches are in keeping with the proposal of language as a communication technology (Dor 2015). The core idea is that the prime function of language is instructing *bearers’* imagination. Language serves the task of inducing the hearer to combine his/her *experiences* in novel ways. This rests on the idea that words’ meaning is essentially an “experiential anchor”, that is, words point at definite experiences, and speakers in a community learn to couple words with those experiential anchors. Thus, a speaker combining words in sentences induces the hearer to *combine experiences* accordingly, and some of these combinations may be *novel* to the hearer. In this sense, language instructs imagination, and may serve as a powerful teaching and learning means.

For what follows it is worth stressing that the considered approaches stress that a great part of what is transferred through language and teaching has to do with, or is grounded in, sensory and motor experiences.

2. The relevance of sensorimotor experience in learning, teaching and language

2.1. How neuroscience can support pedagogy: the sensorimotor experience and embodied cognition

Here, we will collect experimental evidence clearly showing that neuroscience and neuroscientific findings can contribute to, and support, the current debate in pedagogy, the science of education, learning and teaching processes.

So far, we have highlighted that any form of learning is made possible by social interactions the learner must engage in, and that the teacher has the role to share and promote experiences to expand the learners’ competence and knowledge, by mediating those contents that are not immediate and/or transparent. We have also pointed out the role that language has in the educational practice, stressing how some authors forward that language may have developed for educational purposes, namely to support learning and teaching.

Over the last three decades, neuroscience has provided novel findings on the neural mechanism underlying sensory, motor and emotional experiences as well as how these mechanisms also subserve language processing, thus demonstrating that language and experience share common neural mechanisms and substrates. Given that experience and language are the hinges of any learning and teaching processes, it becomes evident that neuroscience may not only contribute to the theoretical debate within pedagogy, but also to implement specific methodological procedures that may favour and support the development of novel learning and teaching.

In neuroscience, the starting point of these developments has been the results of neurophysiological and brain-imaging studies on the sensorimotor system that have «radically changed the traditional view of the motor system as an executive system that merely follows instructions elaborated somewhere else. Instead, the motor system now stands as a probe that explores the external world, for interacting with other people and gathering new knowledge» (Jeannerod 2006: iv). Interestingly, exploring the world, interacting with other people and acquiring new knowledge are what learning and pedagogy are all about.

2.2. At the roots of embodiment: mirror neurons, mirror mechanisms, and canonical neurons

A key turning point in understanding the cognitive role of the sensorimotor system has been the discovery, thirty years ago (di Pellegrino et al. 1992; Gallese et al. 1996), of neurons in the monkey premotor cortex that not only have motor properties but also visual properties. This means these neurons discharge also during the visual presentation of specific stimuli. Based on their visual features, two sets of neurons have been described: mirror neurons and canonical neurons.

Mirror neurons are visuomotor neurons first found in the ventral premotor cortex (known as area F5) of the macaque monkey, and also present in the rostral part of the inferior parietal lobule. Their fundamental property is that they discharge not only when the monkey executes an object-directed action (like grasping a nut with the hand) but also when the animal simply *observes* another individual (another monkey or an experimenter) executing the same or a similar action (Rizzolatti and Craighero 2004). Canonical neurons are neurons that share the same motor properties of mirror neurons but also discharge during the visual presentation of objects that can be grasped and/or manipulated, without the action being actually executed.

2.2.1. Mirror neurons, action understanding and intention coding

Soon after their discovery, it has been ascertained that monkey mirror neurons have the fundamental function of allowing an individual to infer the *goal* of the observed action, as shown in an experiment (Umiltà et al. 2001) where the activity of mirror neurons has been assessed in two different experimental conditions. In one condition, a monkey could observe the entire sequence of an action, such as hand-grasping an object. In the other condition, the monkey could not see the last part of the sequence, which was hidden behind a panel: the animal knew that an object was present behind the panel, but it could not observe the experimenter's hand grasping it. Recorded mirror neurons fired also in this second condition. This has been taken to indicate that mirror neurons are able to infer missing information, namely to re-enact the last part of the action and then, through this re-enactment, to infer the completion of the action itself.

Moreover, some of the mirror neurons not only discharge during the observation of goal-directed actions, but also when actions are presented through their typical *sounds*. Think

of the situation when an individual hears (and recognizes) somebody cracking a nut, in the absence of any visual input (Koehler et al. 2002). These two early findings suggested that the mirror neurons code actions in a quasi-conceptual manner, being sensitive to the goal of the observed action as well as to the presentation (and possibly the processing) of actions, whatever the presentation modality (visual or auditory).

Despite so far there are no single-neuron studies showing the existence of mirror neurons in the human brain, a number of experiments using different techniques have proven the existence of a human mirror neuron system (MNS) whose core areas are portions of the premotor cortex and of the inferior parietal lobule. The human MNS can map an observed action on the same neural circuits responsible for the execution of that action (Fadiga et al. 1995; Hari et al. 1998; Watkins et al., 2003). Moreover, in the human being, such a mirror mechanism is not limited to hand actions but extends to other biological effectors like the mouth and the foot (Buccino et al. 2001; Sakreida et al. 2005; Puce et al. 1998).

The observer's motor competence is crucial for the re-enactment of the sensory motor system during action observation. In other words, the system resonates with actions that are already part of the observer's motor repertoire. Empirical evidence on this line come from a functional magnetic resonance imaging (fMRI) experiment (Buccino et al. 2004a), where human subjects watched movies displaying mouth actions executed by a dog, a monkey and a human being, respectively. Two kinds of actions were presented: biting food executed by the three species, and mouth communicative actions typical for each species (human silent speech, monkey lip-smacking, and dog barking). The results have shown that biting activates the human MNS independently of the observed species, whereas mouth communicative actions activate the MNS only if the agent is a human individual. Thus, the MNS responds to action observation only if the observed action is part of the motor repertoire of the observer, so that it can be matched with its motor representation in the observer's brain. In keeping with these results, another study (Calvo-Merino et al. 2005) has shown that the recruitment of the MNS during action observation is affected by the motor competence of the observer: capoeira dancers, compared to classical ballet dancers, recruit their motor system to a greater extent during the observation of capoeira dance than of classical ballet, and *vice versa* for classical ballet dancers.

These and other findings (Buccino et al. 2004b) clearly show that understanding actions performed by others is fundamentally based on re-enacting one's own motor representations. This is relevant for pedagogy as it implies that mutual understanding already begins from a shared repertoire of motor experiences.

Note that while understanding others' actions we also grasp their intentions, that is, the reasons why individuals perform those actions. Classically, intention understanding has been considered a "purely cognitive" task labelled as "theory of mind" and considered to be subserved by dedicated brain structures (e.g., Leslie and Thaiss 1992; Gallagher and Frith 2003). Developments in MNS research suggest an alternative, though not mutually exclusive, mechanism for intention understanding: We can understand others' intention since observing their actions activates the same neural substrates as when we are animated by the same intentions. In an fMRI study (Iacoboni et al. 2005), participants watched movies where the same action (e.g., grasping a cup) was executed in different contexts (e.g., during or after breakfast). The participants were divided into two groups: one had only to observe the movies; the other was asked to state explicitly the action intention in the different contexts. It turned out that the neural activations were the same in the two groups, including the cortical areas building up the human MNS. These results suggest that others' intentions are not coded by dedicated ("mentalizing") regions but by the same areas processing actions' motor features. The results have also been confirmed by another

fMRI study (Buccino et al. 2007) involving movies of actions whose intentions were realized or not (e.g., a cup is grasped to drink but falls down before the action completes). The results showed that the areas active during action observation and processing of intentions were those included in the MNS. Moreover, when the actions did not fulfil the intentions of the agents, additional areas became active: right temporo-parietal junction, left supramarginal gyrus, and bilateral mesial prefrontal cortex. Though these regions are among those subserving the theory of mind, they are also involved in attentional tasks (such as detecting an unexpected stimulus in a foreseeable sequence or within an otherwise homogeneous set). Thus, the involvement of these regions is quite plausibly explained by the attentional demand of an unexpected failure of an action whose underlying intention has already (and automatically) been spotted. Recent results (Patri et al. 2020) also suggested a *causal* role of the inferior parietal lobule (part of the MNS) in attributing intentions on the basis of action kinematics.

Such a cognitive involvement of the motor system in understanding the intentions behind others' actions is relevant for teaching and pedagogy especially in that, as we have seen, teaching often support the learning process by making the aims of complex behaviour transparent to the learner. As reported below in this paper, classical pedagogists attribute an important role to the construction of meaningful intentions and purposes through the interplay between observed and executed actions.

2.2.2. MNS, imitation and learning

As we have seen, the fundamental property of the MNS is that of mapping observed actions on the neural substrates of the motor representation of one's own action. There is evidence of the involvement of the MNS (along with other brain structures) in *imitation* of actions that are already in the motor repertoire of the subject (Iacoboni et al. 1999; Koski et al. 2002; Nishitani and Hari 2002; Molenberghs et al. 2009).

Does the MNS also support learning *novel* actions, i.e. actions not yet in the observer's motor repertoire? The issue here is whether the direct matching between the observed and executed action still recruits the MNS when the observed actions are not part of the observer's motor repertoire. A study conducted with event-related fMRI (Buccino et al. 2004c) enquired exactly this issue by asking musically naïve people to learn some guitar chords executed by an expert guitarist. Four events were considered: 1) observation of the chords; 2) a pause during which participants had to think to the observed chord and plan its execution; 3) actual imitation of the chord; 4) a few seconds of rest before a new run. The results demonstrated that during observation (event 1) there was an activation of a neural circuit including areas within the MNS. During the execution planning (event 2), the prefrontal cortex, and specifically Brodmann area (BA) 46, was also active. This area is traditionally considered to be involved in working memory tasks (Goldman-Rakic 1996). Indeed, during the actual execution of the chords (event 3) the very same areas were active, along with activation of primary motor and sensory areas. These results demonstrate the involvement of the MNS in the formation of a *novel* motor schema. Moreover, the results also suggest that in the acquisition of a novel motor schema by imitation, the observed action is decomposed in simpler motor segments to be then recombined so to match the observed model. This recombination is performed by prefrontal cortex, BA 46 in particular. In keeping with these data, another experiment (Vogt et al. 2007) with the same design unveiled a greater activation of area 46 in naïve players than in professional guitarists, confirming the role of BA 46 in recombining the simpler action segments by naïve players to build up the complete chord.

Taken together, these results reverse the classical approach to learning novel motor skills (e.g., Schmidt 1991) according to which first the rules and steps regulating the new skills

are learnt cognitively and declaratively (in a sense, “theoretically”) and then the skill is broken down in basic action segments that are eventually executed automatically. The “embodied” understanding of learning by imitation, instead, accords primacy to the motor aspects, attributing a causal role to action observation and execution in acquiring novel motor skills.

We have seen that imitation is a powerful form of learning implying a strict interaction between the model and the learner, and that teaching often serves the purpose of making transparent the opaque aspects of what is to be learned by imitation. The view of imitation emerging from the ascertainment of the involvement of the motor system suggests that the teacher’s task is to facilitate the decomposition of an observed complex action into simpler known segments to be then recombined appropriately by the learner. This is also consistent with the idea that pedagogy supports the learners to build novel skills upon already acquired ones, and that such support involves the *real* actions on both the demonstrator and the learner sides, as we will discuss below.

2.3. Embodied language: the causal role of direct experience

Language is a powerful teaching means, able to support all the teaching forms discussed above (1.1). Moreover, a great part of what is thought at school is language-related, from reading, writing and arithmetic, to more conceptual knowledge. Thus, it is relevant to discuss the role of the neural substrates of sensorimotor experience in language.

Research in embodied language has quite convincingly shown that linguistic expressions referring to concrete actions and aspects of the world activate the same neural substrates involved in executing those actions and in perceiving those aspects. Indeed, there is consistent evidence that language describing actions typically done with a specific biological effector (hand, foot or mouth) recruits the sector of the sensorimotor system where the effector is motorically represented (Hauk et al. 2004; Tettamanti et al. 2005; Aziz-Zadeh et al. 2006; Baumgaertner et al. 2007; Kemmerer et al. 2008; Desai et al. 2010; de Vega et al. 2014). In keeping with this, studies using neurophysiological techniques demonstrated that in processing verbs connected with concrete actions, the sensorimotor system is recruited just 150–170 ms after the auditory or visual presentation of verbal stimuli (Pulvermüller et al. 2001, 2005a, 2005b, 2009). The behavioural counterpart of this early activation is an interference effect. For example, when participants are asked to solve a semantic task on hand related action verbs and are asked to give a motor response with the same effector actually used in the execution of the action verbally described, reaction times slow down (Buccino et al. 2005; Boulenger et al. 2006; Sato et al. 2008; Dalla Volta et al. 2009; de Vega et al. 2013, 2014). Such interference effect has been suggested to stem from competition for neuronal resources (Buccino et al. 2005; de Vega et al. 2013; García and Ibáñez 2016; García et al. 2019): in these situations, the motor system will be slower in giving the motor output, since it is simultaneously processing the meaning of the hand-related actions and preparing the hand motor response to complete the task. In support of this interpretation, during listening to sentences expressing hand or foot actions, Transcranial Magnetic Stimulation (TMS) studies showed a decreased amplitude of Motor-Evoked Potentials (MEPs) recorded from muscles actually involved in the execution of the action listened to (Buccino et al. 2005). Moreover, in a magnetoencephalography (MEG) study, when motor responses are given with the same body part normally used to perform the action expressed by the verb, a weaker suppression of Beta rhythm was found (Klepp et al. 2015; Visani et al. 2022a). Beta rhythm deriving from the motor cortex is characterized by a pattern of suppression and rebound (Pfurtscheller and Lopes da Silva 1999) during action execution, and to a lesser extent during action observation. Hence, weaker Beta band suppression means minor

promptness of the sensorimotor system to perform a specific response, as expected if one assumes a simultaneous involvement of the motor system in language processing and execution of the required motor response.

Studies involving lesions in the motor system (Kemmerer et al. 2012; Desai et al. 2015) or transient impairment of the motor cortex induced by repetitive Transcranial Magnetic Stimulation (rTMS) (Tremblay et al. 2012) further support the causal role of the motor system in processing action verbs.

Reinforcing the idea that the motor system has cognitive functions, two recent studies (Garofalo et al. 2022; Visani et al. 2022b) have shown that the *recruitment* of the motor system in hand action observation neatly overlap *with its involvement* in processing the verbs expressing those same hand actions. Thus, the motor system can be claimed to sustain a “conceptual” understanding of actions beyond a purely sensorimotor resonance.

Taken together, these studies suggest a *causal role* of the motor system in understanding action verbs that cannot be interpreted as a mere side-effect of language comprehension deriving from top-down effects of cognitive areas on the motor system (e.g., Mahon and Caramazza 2005, 2008; Chatterjee 2010).

Converging results have been obtained also about the processing of nouns and adjectives. Behavioural studies (Glover et al. 2004; Tucker and Ellis 2004) have shown that nouns of objects graspable with either precision grip or whole hand prehension facilitated the response if it had to be delivered with the same kind of hand movement on a handle. Other behavioural studies unveiled interaction between hand responses and processing of graspable objects presented either as pictures or as corresponding nouns (Gough et al. 2012; Marino et al. 2013, 2014). A very recent, combined behavioural and MEG study (Visani et al. 2022a) has shown that the involvement of the motor system is also affected by the specific kind of considered object. In particular, graspable natural objects and tools modulate the motor system differently. Interestingly, a similar modulation of the motor system occurs both when the objects are presented as pictures or by their *names*. These results are consistent with the idea that processing nouns of concrete objects relies on the fronto-parietal system and possibly re-enact another set of visuomotor neurons known as *canonical* neurons, first discovered in the monkey brain (Rizzolatti et al. 1988; Jeannerod et al. 1995), and shown to be active both when individuals manipulate an object and when they just observe it (Binkofski et al. 1999; Grèzes et al. 2003). Canonical neurons are most likely involved in sensory-motor transformations of objects properties (e.g. shape, position, potential affordances, etc.) into motor strategies for their manipulation (e.g., reach, grasp, displace, etc.). These considerations suggest that understanding the meaning of object nouns may rely on the sensorimotor canonical-neuron system in the human brain.

Consistently, another study (Gough et al. 2013) considered *adjectives* expressing pleasant (e.g. soft) and unpleasant (e.g. thorny) motor features, and applied TMS to either a hand-closing or a hand-opening muscle. The results show that unpleasant adjectives modulate the hand-opening muscle (actually used to avoid the unpleasant stimuli), whereas pleasant adjectives modulate the hand-closing one (actually used to induce contact with the pleasant stimuli).

Finally, it is worth mentioning that nouns referring to *perceptual* aspects of the world also activate brain areas involved in perceiving those aspects. For example, the word “cinnamon” activates the olfactory system (Barrós-Loscertales et al. 2012) and the word “salt” activates the gustatory one (González et al. 2006). It has also been observed that processing words expressing emotions recruits the same neural structures involved in *feeling* those emotions (Niedenthal 2007; Citron 2012). This suggests that language is embodied not only when expressing motor experiences but also when it refers to perceptual and emotional ones.

Taken together, all the mentioned results clearly demonstrate that processing of linguistic material referring to concrete actions and tangible aspects of the world activate the neural structures involved in the execution of those actions and in the perception of those aspects. Moreover, we have seen that there is compelling evidence that the motor and sensory activations are *causal* to the understanding of words' meaning, i.e., that retrieving meaning from language items depends on re-enactment of the neural circuits underlying the motor, sensory and/or emotional experiences they talk about (Buccino et al. 2016 for review and discussion).

Such results have momentous implications for pedagogy. First, they further circumstantiate, also at the neuro-scientific level, the idea that teaching and learning, in all their forms, and whether or not they are supported by linguistic communication, have primarily to do with concrete, real-life experiences rather than with a-modal, purely cognitive or conceptual contents. Second, the reviewed findings imply that when we talk, we essentially talk about experiences. Hence, this also suggests that understanding each other in linguistic transactions substantially depends on the background of experiences the speakers actually share.

2.4. From concrete to abstract concepts: the experiential ground

A significant part of what human beings learn has a conceptual nature. At school, great efforts are dedicated to convey conceptual knowledge and abstract notions. Can the developments of the embodied approach be applied to these contexts, too? Intuitively, it is much simpler to ground words and concepts like “to grasp”, “to kick”, “cup”, “apple”, or “thorny” in sensorimotor experience than it is for words and concepts like “to appreciate”, “to think”, “justice”, “beauty”, or “sublime”. Words/concepts of the latter kind are said to be abstract in that they seem to be far from sensory and motor experience. Therefore, they constitute an important challenge for the embodied approach (e.g., Gallese and Lakoff 2005).

Empirical evidence about the neural substrates involved in processing abstract words/concepts is relatively limited. However, insightful data are nevertheless available. An early TMS study (Glenberg et al. 2008) found a stronger involvement of arm/hand motor areas when participants had to process sentences expressing transfer of both concrete and abstract objects, rather than sentences expressing no transfer at all. Converging results showing recruitment of hand motor cortex in processing both abstract and concrete verbs have been reported by a later TMS experiment (Scorolli et al. 2012). Two studies (Desai et al. 2011, 2013) assessed fMRI activations during the processing of literal, idiomatic, metaphoric, and abstract language. Sensorimotor activation increased from abstract to idiomatic to metaphoric to literal sentences. The authors conclude that the sensorimotor system is involved also in processing abstract language (including metaphoric and idiomatic expressions), but additional brain areas are necessary to process its meaning as far as the conventional and/or abstract nature of the conveyed message increases.

These results, along with the relative scarcity of clear-cut neural data on abstract language processing, have prompted a variety of attempts to address the matter (for reviews: Binder et al. 2009; Wang et al. 2010; Buccino et al. 2019). The majority of proposed theoretical frameworks can be considered, in one way or the other, as “hybrid models” from the embodiment standpoint. Indeed, they posit that understanding abstract words/concepts is only partially grounded in experience-related sensorimotor neural substrates and also resort to supposed a-modal brain modules processing “pure” language aspects.

A “fully embodied” model for abstract language has been recently proposed (Buccino et al. 2019; Buccino and Colagè, 2022) claiming that the meaning of abstract words and

concepts is grounded in the sensory, motor and emotional experiences of the subjects. According to this model, so-called abstract words and concepts are not such because they are far (or farther) from experience, but because the experiential ground at the basis of their meaning is more *complex*. Specifically, the complexity of the experiences grounding abstract concepts can increase according to:

- The number of effectors involved (abstract language as *effector unspecific*): whereas concrete words are often grounded in one single effector, abstract words usually involve many of them;
- The number of neural systems engaged (abstract language as *multi-systemic*): whereas concrete words are preferentially bound to one modality (visual, olfactory, motor, emotional, etc.), abstract ones often involve many.
- The progressive accumulation of concrete life experiences attached to abstract words/concepts (abstract language as *dynamic*): whereas the meaning of concrete words is generally fixed quite early in individual life (or soon after their first acquisition), the meaning of abstract words is progressively enriched.

In sum, also the meaning and content of abstract words/concepts can be regarded as grounded in the neural substrates of sensorimotor experiences. The key difference with concrete words/concepts would not be a greater distance from experience, but the complexity and richness of the experiential clusters grounding abstractness. This *does* imply that the human brain has structures capable of holding together and combining the varied experiences grounding abstract meaning. However, this does *not* imply (in contrast with the hybrid models) that abstract words are coded in such structures without the key and causal support (the “grounding”) of sensory, motor, and emotional areas.

This idea has received support by two recent meta-analyses on activations related to abstract and concrete concepts (Del Maschio et al. 2021; Bucur and Papagno 2021). The results unveil that several brain regions (including motor, sensory and emotional areas) are active for *both* concrete and abstract concepts. This suggests that processing these two kinds of concepts is not sharply segregated in the brain, and that abstract concepts involve brain circuits subserving individuals’ interactions with the world quite similarly to what happens for concrete concepts. As compared to concrete words/concepts, abstract ones simultaneously recruit several distinct systems, and such systems are recruited at different degrees of intensity depending on the specific contents being processed.

This stance towards abstract words/concepts has several interesting implications for pedagogy. First, it strengthens the idea that learning is primarily concerned with sensorimotor experiences. Secondly, it is consistent with a “constructing” view of learning, according to which newly learned items are built upon already acquired ones. Third, it extends this idea to more complex, conceptual, cognitive, symbolic, and abstract domains, suggesting that the latter are indeed built upon less complex notions. Finally, what we have seen in this sub-section clearly suggests that teaching supported by language is so effective because language may facilitate the learner in *combining background experiences* in more complex, conceptual knowledge. In a nutshell, it can be said that language is crucial for teaching as it is a means to share and combine experiences.

3. Current developments in educational neuroscience and embodied pedagogy

In this section we will focus on two recent developments in pedagogical research. The first, labelled as “Mind, Brain and Education” (Fischer et al. 2007; Fischer 2009) or “educational neuroscience” (Szucs and Goswami 2007), focuses on aspects of *basic* neuroscience research that likely have potential implications and practical applications in pedagogy. The second development aims at synergizing educational research with *movement science* (Abrahamson and Mechsner 2022), upon the assumption that specific

bodily movements may facilitate learning and teaching of abstract concepts such as mathematical ones. These two approaches bear interesting relationships with the embodied approach to cognition and language in neuroscience as reviewed above.

3.1. Educational neuroscience

Research in educational neuroscience starts from the realization that making neuroscientific data about the neural underpinnings of learning processes immediately applicable to educational practice is at the same time a real challenge and a promising perspective (Bruer 1997; Willingham 2009; Goswami 2006).

Three points are to be highlighted in this context. First, given that education specifically interacts with and affects the learners' physical and cognitive growth, the mechanisms of *brain development* are considered a key for translating basic neuroscience research into concrete pedagogical strategies (Goswami and Szucs 2011).

Second, more sophisticated skills *are built upon more fundamental ones*, and the latter are sometimes not intuitively linked with the former. For example, it has been suggested that the acquisition of reading skills (a primarily *visual* skill) crucially depends on phonological processing of *auditory* information conveyed by spoken language, and that problems in reading acquisition (e.g. developmental dyslexia) likely depend on prior deficits in phonological processing (Thomson and Goswami 2008).

Third, educational neuroscience needs to take an *embodied stance* towards learning and teaching. Brain imaging studies have shown, e.g., that «early sensory-motor representations are not replaced by symbolic knowledge [...]. Rather, symbolic knowledge (concepts, words) always depend on the activation of multiple neural networks across the whole brain, including sensory and motor networks» (Goswami and Szucs 2011: 654). Consequently, in pedagogical theory and practice any “mentalistic” and “dualistic” understanding according to which human beings learn with their “disembodied” minds without any important contribution from the body should be overcome (Macedonia 2019).

These insights are consistent with what we have argued to be teaching ultimate goal: facilitating the learners to build novel, more sophisticated skills and knowledge upon already acquired, more basic ones.

Moreover, we have also seen how language can potentiate all teaching forms. The most advanced strand of embodied research in neuroscience is embodied language, which forwards the idea that the meaning of linguistic expressions is rooted in the speakers' concrete sensory, motor and emotional experiences. Thus, embodied language appears to be relevant for educational neuroscience from two viewpoints. On the one hand, according to the embodied perspective, language and teaching appear to share a common sensorimotor grounding. On the other, according to the “fully embodied” understanding of language (Buccino et al. 2019; Buccino and Colagè 2022), also the meaning of highly abstract words is grounded in concrete sensory, motor and emotional experience, so that the latter may turn out to be crucial resources in teaching conceptual knowledge. Therefore, research in the neuroscience of embodied language and cognition currently appears as one of the main sectors of basic neuroscience to be fruitfully applicable to pedagogical research.

3.2. Movement science and pedagogy

As seen above, the neuroscience of embodiment has sprung from the ascertainment of the involvement of the brain motor system in cognitive functions. No surprise, therefore, that bodily movements can play a relevant role in learning. Indeed, recent empirical

studies have emphasized how (i) employing multi-modal channels in presenting students with novel conceptual content (see Ginns 2005 for a meta-analysis), and (ii) allowing students finger-trace instructions and drawings while acquiring mathematical or biological knowledge (Ginns et al. 2016; Smyrnis et al. 2022) turn out in better learning and improved scores in subsequent acquisition tests.

Recent developments further emphasize how specific movements can sustain and improve learning of conceptual knowledge as well. To be clear, the point is not just in the general idea that physical activity has beneficial effects on overall cognitive performance (see Macedonia and Repetto 2017 for a recent review). Rather, the point is that learning by motor experience improves even *non* motor tasks. Recent experiments have shown how performing actions and (meaningful) gestures improve performance in mathematical problem solving (Nathan et al. 2014; Hutto et al. 2015), second language learning (Macedonia 2019; Buccino and Mezzadri, 2015), as well as in first language letter-sound association and reading ability in 5 and 6 year old children (Damsgaard et al. 2022).

Among the contexts that are at first sight less amenable to be understood in embodied terms there is mathematics. However, in the last decades, mathematical pedagogy has been enquired with an embodied stance, giving extremely interesting insights (Abrahamson et al. 2020; Macrine and Fugate 2021; Abrahamson and Mechsner 2022). Recent empirical studies, for example, have shown that introducing mathematical notions after primary school learners perform specific movements and find solutions to spatial perceptual-motor tasks correlates with better scores in mastering mathematical notions with respect to children the notions were introduced to only conceptually (e.g., Abrahamson et al. 2011; Abrahamson and Sánchez-García, 2016).

These findings and perspectives clearly speak in favour of the idea that learning conceptual knowledge crucially involves sensorimotor experience and, more generally, that cognition is strongly embodied even in highly abstract, conceptual contexts. This also implies that developing effective educational strategies and designs should more and more involve the use of the body and of specific perception-guided movements and actions.

Finally, it is worth stressing that the neuroscience of embodied cognition and language appears to be the context upon which educational neuroscience on the one hand, and movement science applied to pedagogy on the other, may fruitfully converge. Indeed, the neuroscience of embodied cognition and language can be regarded as: a) the branch of basic neuroscience most readily applicable to pedagogy, and b) the anatomical and physiological ground of the educational strategies and designs directly employing body movements and perceptually-guided actions.

4. The central role of experience in education: Insights from classical pedagogists

As we have singled out in the last two sections, the novel perspective on the involvement of the sensorimotor system in cognitive functions, the ensuing developments in embodied cognition and language, as well as the development of embodied educational designs have relevant implications for pedagogy. In this section, we will briefly discuss some relevant aspects of classical pedagogical theories (without claiming to be exhaustive), highlighting how they are consistent with the key role attributed to sensorimotor experiences in contemporary neuroscience.

4.1. John Dewey: From sensorimotor activity to intellectual development

The pedagogical thought of John Dewey (1859-1952) represented a radical change in United States education, inaugurating the season of “activism” and progressive education

that broke with the traditional idea of a passive school (DePencier 1967). His thought introduced interesting suggestions on the involvement of sensorimotor aspects in learning. The learning method rests on the assumptions that, in children development, action and movement precede and shape perception, and that conscious states project themselves into action (Dewey 1897).

In *Democracy and Education* (Dewey 1916), the close relationship of intellectual development with motor and sensory activity is deepened. The latter has been erroneously considered as an “intruder” in mental activity, whereas in reality, the senses are «gateways and avenues of knowledge» (Dewey 1916: 166). According to this approach, students have to act upon the objects if they intend to know and learn. This is the root of the contemporary slogan: “learning by doing”.

The “doing”, which specifically includes the motor acts, extends its role up to the modification of the context and the environment in which teaching and learning occur. Schools should be equipped so to reproduce real-life experiences, as in this way «information is vitalized by its function; by the place it occupies in the direction of action» (Dewey 1916: 190).

Dewey’s concept of experience discloses a holistic approach to education, in the sense that it is based on the interaction between the human being and the world (Hohr 2013). When we refer to “having an experience”, the interaction process is emphasized, which assumes some form of action. The interaction between the internal and the objective sides of experiences confers educational function and force to experience itself (Dewey 1938). Experience is closely related to the concrete situation and the real interactions involved, allowing individuals to attribute ever new *meaning* to their internal states. Sensorimotor experience takes on a key role in learning as *meaning* results precisely from perception and actions (Dewey 1916). However, observation is not enough. The significance of what we perceive «consists of the consequences that will result when what is seen is *acted upon*» (Dewey 1938: 39). So understood, meaning formation is rooted in active and concrete experience, quite coherently with embodiment in current neuroscience, and specifically with how we have seen meaning is attributed to linguistic expressions.

Dewey’s pedagogical thought is also attentive to the social dimension. Being rooted in sensorimotor experience the way we have seen, learning and teaching disclose possibilities of resonance, and for understanding the meaning attributed *by others* to the same actions and experiences. *Imitation* is crucial, especially if conceived of as a means to improve one’s own competence starting from already acquired bits of skills to the aim of developing effective actions (Dewey, 1916).

Acquisition of language works similarly. Dewey (1899) emphasizes language as a social process through which speakers can share their experiences. Meaning is attached to linguistic expressions in the same way as things acquire significance, i.e., by being used in a given way with other (adult) people in common experiences and shared activities (Dewey 1916). Thus, according to Dewey’s pedagogy, motor and interactive experience grounds language learning, too.

4.2. Maria Montessori: Education beyond the mental

Maria Montessori (1870-1952) brought about a paradigm shift in education, according to which it is no longer “the mind alone” to be educated (Montessori 1949). The pedagogical proposal is the renowned *Montessori Method*, whose basic tenet is that the school is not a place where knowledge is transferred but «an environment specially prepared for the children where the children absorb whatever culture is spread in the environment without anyone teaching them» (Montessori 1949: 16). Montessori’s thought clearly anticipated

some of the current educational priorities, such as education to the senses and movement education.

Sensory education is particularly relevant (Montessori 1912). It becomes a precise purpose, pursued through specific exercises proposed to the children; the organization of time, space, and learning experiences are structured to the purpose. All this stems from the conviction that the development of the senses precedes that of the higher intellectual powers (Montessori 1948).

The emphasis on the senses is often accompanied by the relevance of the active, motor and action-related aspects (Montessori 1912). Against the prevalent neglect of movement education at that time, the *Montessori Method* emphasizes movement as a means of expression and relationship in view of higher intellectual development: «mental development must be connected with movement and is dependent on it» (Montessori 1949: 202-3). The manual activities proposed to children are related to the development of controlled and finalized movements, so that the motor system can work as an experience activator.

Finally, in *The Absorbent Mind*, Montessori considers language in its social value, as «the instrument of thinking together» (Montessori 1949: 157). Reading and writing are valued in view of intellectual development. Learning to write is structured, according to the *Method*, so to stimulate motor activation. The letters are touched, felt, drawn, handled: «writing is an act in which the psycho-motor mechanism predominates» (Montessori 1949: 359).

4.3. Lev Vygotskij: Constructive and social education

Since the 1960s, the pedagogical thought of Lev Vygotskij (1896-1934), has become the inspiration for a theoretical turn in psychology. Vygotskij's advocacy for a solid *physiological* foundation of psychology and pedagogy (Vygotskij 1992) is also worth to be stressed here. The first relevant element is Vygotskij's proposal of a new learning scheme: «the real movement of the development process of infant thought is accomplished not by the individual to the socialized, but from the social to the individual» (Vygotskij 1986: 36). Vygotskij regards child development as a socio-historical process where the specific socio-cultural context is relevant to the learning process to the extent to which it poses new demands and *new goals* to the learner (Vygotskij 1986).

From this position, Vygotskij derives a novel pedagogical postulate according to which learning precedes development: «The child masters certain habits and skills in a given area before he learns to master them consciously and deliberately» (Vygotskij 1986: 184). These insights are in keeping with the relevance of movement science for pedagogy as well as with the role played by covert sensorimotor processing involved in action and intention understanding as unveiled by embodied neuroscience.

A relevant notion following from the postulate is the *zone of proximal development*. It is understood as the differential between the current development of the child's psycho-intellectual functions (as resulting from already accomplished specific learning processes) and the potential development (Vygotskij 1986). To enquire into this notion, Vygotskij introduces the children to a problem-solving task too difficult for their age, and observes how they solve the task, so to determine the potential level of development. The outcome of the process is that, thanks to collaboration and aid from adults, some of the children indeed solve the task (Vygotskij 1986). Education, thus, consists in putting into action the potential abilities of the learner and in directing the latter to use those potentialities effectively, through active engagement (Kostjuk 1956). This point is clearly in keeping with the understanding of teaching as a modification of the expert's behaviour aimed at facilitating learning by pupils. Moreover, working on the children's *zone of proximal*

development involves *imitation* as a means to promote maturation of some practical or cognitive functions (Vygotskij 1986). This is akin to the understanding of imitation learning by current embodiment neuroscience.

Finally, the success of the imitative process also depends «on the unity of speech and action in education. [...] Education that separates words from deeds is a failure» (Kostjuk 1956). The imitative process, should then be understood as the *co-construction of experience* (Vygotskij 1986). Embodied language, especially according to the “fully embodied” model mentioned above, is currently reaching the same conclusion starting from neurophysiological considerations: language is fundamentally a refined means to share experiences.

It is worth briefly mentioning also that Vygotskij’s pedagogy has found an interesting application in Italy by Loris Malaguzzi (1920-1994), the Italian psychologist and pedagogist who, in 1951, co-founded the Municipal Psycho-Pedagogical Medical Centre of Reggio Emilia, aimed at children and young people with disabilities and school problems. In this context, Malaguzzi invents the “experimental laboratory school”. Malaguzzi’s approach to child education has spread internationally, and also played a role in the diffusion of Vygotskij’s pedagogy (Rankin 2004; Malaguzzi 1998). The laboratory school pays particular attention to motor education and to expressive languages. The dimensions of activity and manipulation to guide learning within a dedicated *relational* context are the hallmark of Malaguzzi’s preschools, where the teacher primarily supports children’s own experiences (Malaguzzi 1994).

4.4. Paulo Freire: Education in situation

Paulo Freire (1921-1997) organized a method for adult literacy in Brazil during the 1960s. His thought became, already during the 1970s, an international reference-point. Freire’s method rests on the assumption that social dialogue is an essential prerequisite for literacy (Freire 1967). For this reason, the process starts from the drawing of a real-life situation (see also Freire 1970), upon which the dialogue among the students (who were mainly adults) is stimulated. Hence, the students generate words/concepts that describe and analyse the situation, starting from the culture in which they are immersed. In the process, help from the debate coordinator allows to recognize “generating words” that capture *common experiences* (Freire 1967). Once the dialogue among the students develops, the coordinator makes the generating word visible through writing. In this way, the method takes the students from their experiential background as captured in the depicted situation and analysed in the dialogue to their “zone of potential development”, i.e., to the *written* word that at this point emerges almost naturally from the process. Only once the process has reached this point, formal aspects of literacy are addressed, such as the breaking-down of words into their “pieces”, i.e., syllables and phonemes, thereafter used to recognize other words.

Just as Montessori’s method starts from the surrounding environment, Freire inserts the words into the real-life situation-drawing that represents them. Freire, therefore, starts from the significant historical and cultural *experiences* of the illiterates to co-construct the vocabulary. Moreover, in keeping with Vygotskij’s point that the social milieu anticipates individual learning, in Freire’s method the social and cultural context made visible in drawings takes the illiterate at a first individual learning. This is a clear-cut implementation of the idea that more complex skills and notions are built upon the fundamental experiences of the learners.

5. Conclusion

In the contemporary debate on the role of pedagogy, there is a fundamental need to bridge the gap between neuroscience and educational practices. Indeed, recent neurophysiological and psychobiological findings disclosing how the brain is endowed with neural mechanisms allowing individuals to share experiences with others and interact with the environment can offer a solid and productive empirical ground to pedagogy. As a matter of fact, in the learner's perspective, these findings support the exploitation of observation, imitation, and social interactions as learning tools; in the teacher's perspective, they ask for an empathic attitude towards learners with the aim to promote those learning tools in any educational contexts. What appears urgent is that some intuitions of path-breaking pedagogists in the past should become *routine habits* of educators based on the evidence that the human brain evolved and works as a “social engine”, exploiting motor, sensory and emotional experiences to build up a conceptual, embodied knowledge of the world. This approach has already led to interesting results in learning/teaching mathematics, second language, reading skills, etc. New scenarios are opening up for educational practice. Just as an example, virtual and immersive reality is already an established tool in the rehabilitation of motor impairment in different neurological patients (e.g., Demeco et al. 2023 for a review). From our standpoint, it also has the potential to promote an experiential dimension of learning in different activities, including basic school subject matters, as well as sport, playing musical instruments or even medical and surgery practices. Moreover, the notion that linguistic meaning, even in complex and high-level conceptual contexts, is rooted in concrete sensory, motor and emotional experiences should affect pedagogical research, and encourage educational practices in which linguistic expressions never lose their primary link with concrete, real-life experiences. We wish the present article may encourage these processes.

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