1. Translating neuroscience into the design of systems, experience and interaction: new perspectives for designers

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Advancement in neuroscience represents one of the most fascinating scientific endeavours of recent decades. Neuroscientific progress contaminated a wide range of disciplines spanning from epistemology (e.g., phenomenology of perception) to economics (e.g., game theory). In addition, neuroscientific progress reveals new challenges for ethical and anthropological issues (e.g., free will, end-of-life, responsibility, etc.). More recently, design and neuroscience have also found several points of contact: User eXperience (UX) and emotions; affordance and motor planning; User Interfaces (UI) and working memory management are some of the dyads relating the two disciplines. However, a theoretically-robust and experimentally rigorous terrain to explore and fully exploit the potentiality of this synergy is still lacking. Translating neuroscience into the design of systems, experience, and interaction is an emerging frontier: illustrative issues in which neuroscience can provide significant insights for designers will be presented and discussed here.

1.1 Non-motor functions of the *motor system*

Research in brain sciences clearly ascertained that the so-called *motor system* is not only involved in purely motor functions (motor control, motor execution), but also plays a critical role in more complex, higher, non-motor computations (Rizzolatti and Sinigaglia, 2016). This represents a fundamental turning point in neuroscience, for the understanding of brain architecture supporting human behaviour. This also signifies implies a fascinating paradigm shift for designers, being a totally new way through which we consider – from a neural perspective – the multilayered interaction between individuals and objects.

Among neuroscientists it is a well-established idea that our brain recruits very similar neural resources when it encodes the execution of a specific action (grasp-the-bottle-to-drink), and when it encodes the simple observation of the same action performed by another individual. In other words, at the neural level there exists a sort of *motor representation* of a specific action, regardless of whether this action is first-person-executed or simply observed. The neural resources supporting the elicitation of specific motor representations have been often referred to as *action execution – action observation network*, or *mirror mechanisms* (Bonini *et al*., 2022). Motor representation is a key construct in motor neuroscience. Of particular note to designers is that motor representation proves how the *motor system* goes well beyond purely motor functions, being characterised by significant properties of generalisation, abstraction, and socially-oriented tuning (Casartelli *et al*., 2018). So, what does this mean?

First, it means that motor representation does not encode only very detailed aspects of an action (the peculiar precision grip to pick a small pin), but it entails the recruitment of very similar neural resources even when two actions with the same goal are performed with different effectors (press-a-button with the right or left hand, or with a foot, or with a stick). Thus, regardless of this action, a specific neural representation of pressing a button is observed or executed with the right/left hand, and even with the right/left foot. In these terms, we can refer to the generalization property of the motor representation. The study of these generalised patterns could be very effective in Human-Machine Interface design (HMI) or even in the design of objects of everyday life. This also shows how the *motor system* has effector-independent encoding properties. Neuroscience is providing the reference paradigms to implement the task's affordance.

Second, convergent studies suggest that motor representation shows a relevant abstraction property, being able to encode, for example, the *value* of the grasped object (Caggiano *et al.*, 2012). More simply, neural activations supporting motor representation can be modulated by the value that agent attributes to the grasped object (banana or pretzel for monkey; wedding ring for bride or jeweller). This means that the *motor system* sees objects not only in terms of things-to-be-grasped, i.e., in concrete *physical* terms. The *motor system* also catches abstract features of an object, i.e., its axiological property and immaterial significance. In this sense it becomes clear how cognition (and the neuroscientific studies on this integrated approach to the object matching the mechanics of shape/grasp fitting with the not-material value of the object) contributes to the design for the usability process.

Third, at the neural level the motor representation of a daily-life action (move-the-candy) is modulated also by the specific *recipient* (move-the-candy-in-the-box vs move-the-candy-in-Tom's-hands) even in cases where the two actions are largely comparable from a biomechanical perspective. This implies that our *motor system* can modulate its activations according to the presence of social (Tom) or non-social (box) recipients (socially-oriented tuning property). In turn, this suggests that the *motor system* is sensitive to the presence of other individuals (that may also be potential co-agents in a future joint action), and it has an interpersonal motor mapping of the surrounding space (Caggiano *et al.*, 2009; Danjo *et al.*, 2018; Stangl *et al.*, 2021).

Why should generalisation, abstraction, and socially-oriented tuning properties of motor representation be of interest for designers? Why should this at-first-glance "technical" neuroscientific issue be relevant to multidimensional analyses that characterise the designer's effort? They are pivotal because they force designers to

also consider subtler, non-motor properties of the *motor system*.
In turn, this promotes a deeper understanding of the way through which human interaction with objects (e.g., acting with; acting upon; etc.) can be projected. Taken together, these findings clearly demonstrate how the motor system is very *smart*. If the motor system is to be a mere executor of commands coming from other brain areas, we should also reconsider the connection between the human motor system and the object (please refer to the construct of embodied cognition, Gallese and Sinigaglia, 2011). Below are concrete examples of how designers are called to tackle challenges such as these.
One of the most studied and fascinating properties of the human motor system is its ability to plan actions (e.g., the very early ability to combine the activity of muscles, joints, fingers to grasp a little ball, Sylos-Labini *et al*., 2020), and then execute them apparently effortlessly. Efficient motor planning is pivotal to maximise our interaction with objects, environment, and other individuals. A former, naïve, view considered motor planning as a rigid process entailing a sort of step-by-step computational approach; in other words, it considered motor planning as the ability to support the passage from A to B, or from B to C (and in the case of complex actions, also from C to D, or from D to E). Significantly, this view considered A-B, B-C (C-D; D-E; X-Y; etc.) as independent steps. Benefitting from the discoveries ascertaining subtler and more complex properties of the motor system (generalization/abstraction/social-oriented tuning), it has been demonstrated that individuals incorporate what they have to do in the final part of the action (B-C) even from the initial phases of that action (A-B). This ability has been defined as distal planning or second-order motor planning (Rosenbaum *et al*., 2012) (for an illustrative daily-life case, see Figure 1). This basically indicates that the A-B step is not independent from the final outcome B-C. Supposing you have to move one dice from the point B into a small box placed at the point C1, and alternatively to move the same dice from B into a large box placed at C2 (C1 and C2 are spatially the same point, only the dimension of the box changes). If you start moving your hand from the starting-point A, then distal planning theory implies that the biomechanics of the A-B act is not independent from the outcome (small box vs large box). More simply, when you execute the A-B part of the action, your brain

is already taking into account the final outcome C (C1_small box or C2_large box), and accordingly it will drive the kinematic profile of your action (i.e., A-B will be faster in the case of the large box because it is easier to put the dice in a large box, and slower in the case of the small box because it is more difficult to put the dice in a small box).

Why should this be relevant for designer? The answer both stimulates and touches the domain of affordance. When designers analyze the best way to project the handle of an object, they should consider not only the proximal outcome (to grasp the flowerpot, but also its potential distal outcome (to place it on the bottom or top shelf).
If the flowerpots generally placed on the top shelves, the designer should consider that it has to be grasped by its lower part.
In contrast, if it is generally placed on the bottom shelves, the designer should consider that it has to be grasped by the upper part (i.e., in biomechanics, the *grasp height effect* states that when one grasps an object to move it to a new position, the grasp height on the object is inversely related to the height of the target position; see Ansuini *et al*., 2018). Empirical observations probably led many designers to already adopt this strategy or recommendation, but neuroscience provides robust and experimental support to this practice (Figure 2).
In contrast, other features of human brain functional architecture remain basically unexplored by designers. An additional illustrative example is presented in the following section.

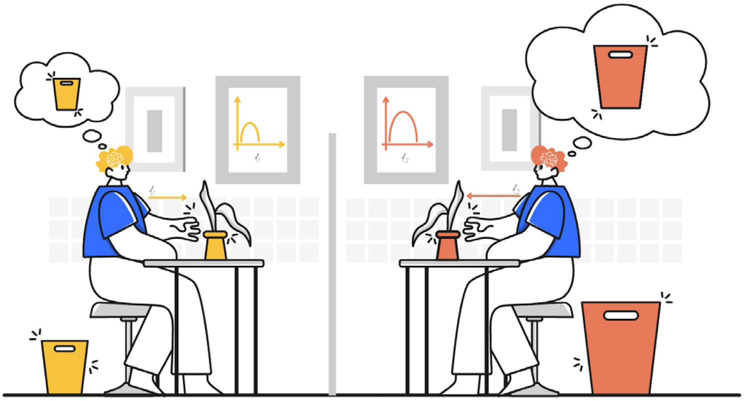

Figure 1. Distal planning maximizing the interaction with objects, environment, and other individuals.

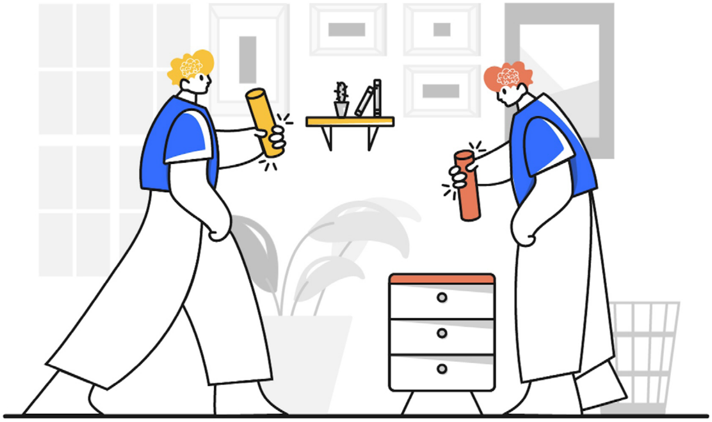

Figure 2.
Grasp height effect: grasp height on the object is inversely related to the height of the target position.

1.2 Predictive brain: expectations drive both action and perception

Although walking is generally considered a taken-for-granted ability, it is evidently not the case for everyone. For innumerable reasons (e.g., Parkinson's disease; stroke; neuromuscular disease; ageing; muscular strain; etc.), an individual can experience temporary or chronic difficulties in walking. However, even limiting our analysis to healthy individuals, proficiency in walking should not be taken-for-granted. A deeper analysis can show how walking can be complex and multifaceted. Indeed, healthy individuals continuously have to adjust their gait pattern to accommodate environmental (asphalt or dirt road) and contextual (crowded street or isolated route) requirements (Matthis *et al*., 2018; Santuz *et al*., 2018). This implies the combination of a multilayered set of non-motor computations involving – among others – sensory and perceptual processing. There are further arguments supporting the idea that walking is not just related to our legs. First, influential studies have demonstrated that any cognitive effort during walking (e.g., count; remember the itinerary; remember your friend's birthday date; etc.) have an impact on the gait's biomechanical pattern. This phenomenon has been explored in the so-called *dual-task* experimental designs (Camicioli *et al*., 1997; Lindenberger *et al*., 2000). Clinically, dual-task design is widely employed to promote early detection of neurocognitive decline in ageing or prodromic signs of neurodegenerative disease (Ting *et al.*, 2015). Second, and probably more surprising, walking is largely influenced also by our expectations. Healthy walkers efficiently combine prior knowledge concerning the peculiar features of the terrain to maximise performance and safety (e.g., this woodland trail is risky when the terrain is slick; this morning it was raining, now it is not raining, but it is cold and cloudy so the terrain will be damp; it will be dangerous, so I have to be prudent). Notably, it is not necessary for the expectation to be grounded on a well-structured and conscious thought. Normally (and automatically) we modulate our steps passing from asphalt to lawn when descending from the pavement.

A recent study by Ciceri *et al.* (2023) showed that even a simple auditory stimulation evoking a specific risky or safe scenario (e.g., seaside during a autumnal lightning storm or sunlit and bright summer day) is enough to modulate the biomechanics of walking. This is in marked contrast with participants walking on a treadmill (i.e., the terrain and, more generally, all *physical* features were virtually identical in both scenarios), which suggests that current motor performance is influenced not only by *physical* features of the terrain or the individual's condition (e.g., fatigue; hurrying), but also that the individual's expectations play a fundamental role in modulating the biomechanics of walking (Figure 3). Thus, by referring to the impact of expectations on walking activity, we also foster an additional neuroscientific insight for designers that concerns the construct of *predictive brain* (Clark, 2013; Teufel and Fletcher, 2020).

Figure 3.
Walking is not just matter of using our legs: influence of neurocognitive, social and environmental factors on our behaviour.

Neuroscience suggests that how one individual perceives an object depends only partially on the physical characteristics of the object (small, rough cold, etc.) and the environment (darkness, chaos, etc.). A better understanding of how individuals' brains sample and organise information, and then plan interactions with objects, can effectively represent a turning point for designers. Notably, this is especially true in domains such as health design in which clinical populations may have both particular needs or limitations in dealing with objects (seeing, grasping, moving, etc.), and potentially altered predictive mechanisms (Sterzer *et al.*, 2018; Chrysaitis and Seriès, 2023). Considering the very real example of grasping a bottle of milk from the refrigerator for breakfast, how you grasp it certainly depends on its shape, weight and dimension. However, how you grasp it also largely depends on the expectation that it will be cold (you cannot be sure, but it very likely has been there all the night. So, it should be cold…). Your expectation does not concern a *real* and *immutable* feature of the object, but it concerns your subjective belief concerning the temperature of the object. Designers should be aware that one individual's understanding of the world largely depends on her/his specific and idiosyncratic expectations. In other words, designers should be aware that perception is an active and constructive process, as strongly supported by robust experimental evidence (Teufel *et al.*, 2020). In turn, in considering user experience designers cannot neglect the fact the how one individual interacts with an object strongly depends on what she/he expects from that object. Is it possible to map any individual expectation, and in turn set accordingly the project of our vessel? Obviously, it is impossible. First, any individual is unique; and her/his expectations are also unique. Second, individual expectations are not set in stone, they are dynamic across time. However, designers could consider the fact that – generally speaking – specific environmental or personal situations usually result in *common* expectations (e.g., if the milk is in the fridge, it will be cold; if the waiter is bringing the pizza to your table, the plate will be hot).

Focussing on expectations in sensory and perceptual domains, predictive brain framework seems to face a double challenge (Press *et al.*, 2020). From one side, it stresses the need of maximising veridical percepts (percepts that reflect the true state of the world).

From the other, it underlines the crucial role of informative percepts (percepts that convey what we did not already know).
The term percept basically refers to effective sensory/perceptual phenomena that an individual has experienced from the first-person perspective (Casartelli, 2019).

In recent years, many computational models that tried to explain how expectations can render perception as either veridical or informative seemed to imply that these approaches were mutually exclusive. To maximise a veridical percept, a common hypothesis is that perceptual experiences are dominated by expected events (if you are watching a documentary on the North Pole, the white animal will be a polar bear, and not a sheep). This would imply that individuals increase the accuracy of their perceptual representations by biasing them according to prior expectations (de Lange *et al.*, 2018). In contrast, to take advantage of an informative percept, a hypothesis is that perceptual experiences of common or expected events are suppressed (e.g., if you are grasping a valuable vase, you will reduce the processing of the predicted sensation of the vase touching your fingers, and this will allow you to be particularly responsive to unexpected events like the vase slipping). The prioritisation of unexpected events promotes the updating of an individual's models and beliefs (i.e., what it did not already know) (Richter *et al.*, 2018), and this may help to explain why we cannot tickle ourselves. Both computational models are efficient in explaining one part of the system. The problem is that our interaction with, and our interaction in, the world seems to need both a propensity that optimises veridical percept (i.e., biasing towards expected events), and one that optimises informative percept (i.e., biasing towards unexpected events). A recent theoretical model suggests that these propensities should be considered together, and we should focus on their temporal dynamic: individuals are initially biased towards processing expected events (it is parsimonious to limit the computational cost of brain operations, as also suggested by heuristics in UX domains), and individuals subsequently switched their resources to upweight events that are particularly surprising (the tendency to be alerted to face unfamiliar scenarios is a well-preserved evolutionary development) (Press *et al.*, 2020). If they are to embrace this dual-process model, an interesting insight for designers will concern the way they address the so-called *perceptual bistability* (PB).

A naïve view would consider any object (e.g., a vase) simplistically as an object (i.e., the vase that my son gave me). However, it is obviously an oversimplified tale. A classical case study in neuroscience concerns the presence of one specific stimulation that can result in multiple perceptual outcomes (Blake *et al*., 2002; Rassi *et al*., 2019). This phenomenon has been referred to as PB. Although it can refer to distinct channels (auditory, tactile; proprioceptive), for the sake of simplicity we focus here on visual PB. Eminent examples of visual figures resulting alternatively in two perceptual outcomes are the Necker cube, the Schroeder stairs, and the Rubin's vase-face illusion (Wade, 1996). Compelling studies demonstrated that the perceptual switch (e.g., face-vase / vase-face) is predictable from brain oscillatory activity and connectivity (Rassi *et al*., 2019), and more generally is regulated by the dynamic interaction between low-level (shape; colour; brightness; etc.) and high-level (memory; lexical cue; etc.) factors (see also Ronconi *et al*., 2023). Among high-level factors, a significant role is played by expectations (if you are in a flower shop, you will be probably biased to see a vase). Designers should benefit from neuroscientists' efforts in elucidating perceptual experience of bistable stimuli. To perceive a vase is not he mere connection between the visual human ability and specific "physical" features of the object (e.g., shape; material; etc.). Objects are not mere things-to-be-grasped. Visual perception of the vase is an active and constructive process.

1.3 Conclusion

Translating neuroscience into design of systems, experience, and interaction is a promising endeavour to provide new reference paradigms and scientific soundness to designers' creativity. Designers already employ some neuroscientific principles in their work, probably coming from empirical observations but without the theoretical generalisation derived from the in-depth comprehension of the neural and computational architecture of these principles. To prioritise the synergy between neuroscience and design can help to fill this gap. The application of neuroscience of motor and logical interaction improves the design and affordance for our living environments and related technological systems. In this sense the social impact of such an approach could be analysed in its importance. The presented examples of neuroscientific principles seem relevant to support this concept. The *motor system* has *smart* properties and it is not limited to motor execution and motor control, so the gesture is driven by intention, by the required affordance, and by the shape and material of the object. In this preparation to use, perception (visual and tactile *in primis*) is an active process strongly contributing to the physical and cognitive interaction (and use) of objects, and it is where individual expectations play a critical role. All these facts indicate how designers can exploit this richer understanding of the neuroscientific bases of human interaction to design the best fit or affordance, user experience and user interface even in complex human-machine systems. Thus, a stronger synergy in neuroscience and design is a promising perspective on providing scientific evidence to good design and good design for everyone.

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