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Abstract

Vision is the most synthetic sensory channel and it provides specific information about the relative position of distant landmarks during visual exploration. In this paper we propose that visual exploration, as assessed by the recording of eye movements, offers an original method to analyze spatial cognition and to reveal alternative adaptation strategies in people with intellectual disabilities (ID). Our general assumption is that eye movement exploration may simultaneously reveal whether, why, and how, compensatory strategies point to specific difficulties related to neurological symptoms. An understanding of these strategies will also help in the development of optimal rehabilitation procedures.

1. INTRODUCTION

The adaptation of vision as a tool for writing and reading is a recent cultural development, as discussed by Land (2009). During the early stages of primate evolution, the basic role of vision was to provide fundamental information needed for adaptations of vital importance such as hunting, food gathering and shelter building. More generally, vision plays a prominent role in the exploration contributing to spatial cognition, even in nocturnal rodents such as laboratory rats (Schenk, 1995). In rodents, the neurological basis of spatial representations has been approached from the recording of hippocampal unit activity (see, for ex., (Poucet, 1993), which are closely related to body localization and orientation. A predominance of vision over olfaction for spatial orientation in a macrosmatic and nocturnal species (Lavenex & Schenk, 1996) emphasizes the advantage provided by a sensory modality that enables the localization of distant landmarks, whereas olfactory information must be combined with locomotion to inform about actualized position. In monkeys, these units are clearly related to where subjects are looking at in their environment (Rolls, 1999). Hence, primate eye movements may shed some light on the brain's cognitive mechanisms in a broad sense, since gaze control is directly related to anticipatory processes and executive functions.

From an ontogenetic perspective, vision cannot be approached as a mere physiological process because it is a combined product of biology and culture. As highlighted by Alain Berthoz (2005, p. 252): *"It is the child's first interaction with the world. Before walking with his legs, he walks with his eyes."* This interaction requires and stimulates developmental plasticity, as revealed by the early imitation behavior reported by Andrew Meltzoff. This means that we are faced with what Berthoz called "simplexity" (2009), i.e., an assembly of simple rules organizing complexity in living organisms. This assembly is functionally mediated in such a way that “despite the complexity of natural processes, the brain can prepare an action and anticipate its consequences”. For A. Berthoz, these processes contribute to a sense of coherence and continuity, even at the cost of a detour *(2009, p.12).*

Essentially, the integration of visual information to support action is mediated by a cooperation among large specialized modules: the gaze system, the motor system and the visual system, all three under the control of a schema control system (Land, 2009). This diversity is integrated by simplexity rules that unite numerous feedback loops in an adaptive style. The emergent style can be assessed using eye movement recording.

Various categories of intellectual disabilities (ID) are associated with distinctive or abnormal features of visual exploration strategies. These might be a direct consequence of neurological deficits in the organization of actions or intentions. Disabilities might also be secondary to cognitive deficits during the development and acquisition of visual exploratory strategies. Understanding how a handicap might modify visual signal integration and subsequent strategies for collecting information should shed some light on cognitive deficits otherwise inaccessible to a comprehensive approach. Essentially, eye tracking is currently used in a variety of research to investigate visual and cognitive processing in individuals with ID (e.g. individuals with autism spectrum disorders, Down Syndrome, intellectual/ developmental disabilities of unknown origin, William’s Syndrome, Rett’s syndrome, and Fragile X syndrome (Hanley, Riby, Caswell, Rooney, & Back, 2013; Owen, Baumgartner, & Rivera, 2013; Riby & Hancock, 2009; Wilkinson & Light, 2014)). Furthermore, as Light & McNaughton (2014)**,** clearly expressed, one should insist on the importance of understanding the underlying processes in order to maximize individual performance. For these authors, analyzing basic visual cognitive processes is fundamental in order to offer effective interventions.

First, we will revisit the process of spatial learning and detection, and then we will develop its relation to eye movements. Finally, we will consider the specificity of visual perception deficits in ID people. This is not to say that we propose a static diagnostic based on specific eye movement impairment, such as would be obtained from a single biomarker or some endophenotype. Rather, we think that eye movement strategies used by ID people in real life situations might reveal specific dimensions in altered behavioral and coincident cognitive adaptations. In this sense, “abnormal” eye movements do reveal a high cost strategy contributing to the burden of the mental handicap. A re-educative therapy aimed at reorienting this compensatory strategy should reduce the handicap, or, at least, its nuisance. Since eye movements are under cognitive supervision, one can expect that the reorganization of such “motor strategies” would in turn improve cognitive activity, or at least reduce its load.

2. Spatial orientation and detection processes

By definition, habituation is the decrease in responsiveness to a repeated stimulus. Classically, it is considered to be the simplest and most primitive form of learning, common to all living beings (Chapouthier, 1988; 1999). The response triggered by a stimulus is a combined function of its contrast, i.e. its intensity relative to the current background, and also its contrast with known or familiar stimuli (Berlyne, 1960). This second dimension addresses the question of memory. To relate the observed reaction to higher cognitive processes, one should first discriminate between noticeability and novelty, as proposed by O’Keefe and Nadel (1978). *Noticeability* proceeds from the contrast between a stimulus (sound, light, object, etc.) and any memory representation of it. It can thus be regarded as a basic cognitive process. Moreover, as any stimulus is necessarily associated with its context, whether spatially or emotionally defined, its *novelty* refers to the lack of memory for this particular association (the new position of a piece of furniture in one’s kitchen, an odor in a given context), even though both the specific item and its context are already familiar. Naturally, novelty and noticeability are interactive dimensions, since the novelty of an object in a familiar place contributes to the sensory salience of this object via the orientation reaction and its neural basis.

Context can be a particular circumstance. It can also be “a position in space,” a place. Spatial representations require memory as an essential feature, and hippocampus-dependent spatial memory is commonly considered to be a phylogenetic precursor of human episodic memory (Burgess, Maguire, & O'Keefe, 2002). Spatial orientation is the basic process that allows subjects to code and remember the relative position of different places in an environment. Its higher cognitive dimension is accounted for by the fact that a “cognitive map” enables new decisions such as short cuts and detours (Tolman, 1948). In this sense, spatial orientation may reveal high order cognitive processes. To quote Neisser (1976), however, such maps are « …not pictures in the head, but plans for obtaining information from potential environments ». This knowledge is expressed by eye movement control. Exploratory behavior is triggered in a completely new environment or in response to the detection of modifications relative to the previously familiar state of the environment. Spatial orientation thus leads primarily to basic environmental knowledge and then to accurate spatial novelty detection.

An environment in which one has never been before triggers the gathering of spatial information through visual and locomotor exploration (Welker, 1961). Bottom up and top down cycles are integrated into a helical gear with low order automatic processes contributing to cognition, while being in the same time under cognitive supervision. The alternate movements between new and familiar regions correspond to a real dynamic of exploration. Novelty is a drive for exploration leading to novelty reduction during exploration cycles (Neisser, 1976). At the same time, the elaborated knowledge animates future curiosity.

The organization of exploration relies on a reference head orientation, as emphasized by very precise head direction neurons found in several brain areas (Langston et al., 2010). Visual exploration enables self-orientation and an analysis of the visual world in order to react appropriately (Muri, Pflugshaupt, Nyffeler, von Wartburg, & Wurtz, 2005). Gaze is linked to orientation, possibly intention "I am going to where I am looking at" (Berthoz, 1997). Visual exploration is mediated by parallel processing of elementary features carried out through categorical (color, contrast, etc.), geometric (shape, length, outlines, etc.), and dynamic (movement) segregation. Semantic memory facilitates the identification of subsequent objects, context episodic memory favors their anticipation. These information are combined in such a way as to eventually facilitate action and decision making (Berthoz, 2003, p. 184).

Our proposition is that a detailed analysis of eye movements during exploration in "natural environments" should reveal cognitive memory processes, that are partly remote from verbal conscious declarations.

3. How to relate eye movements and spatial memory?

When studying a visual scene, eye movements, fixation points, and the duration of gaze fixation offer objective clues to the mental work of processing visual information, in an automatic or controlled way. As Rayner, Smith, Malcom and Henderson (2009) have established, there are no separate oculomotor systems for watching scenes, during visual research or reading. Thus, the neuronal mechanisms underlying oculomotor activity are not task dependent. Rather, they reveal fundamental processing guiding and organizing exploratory movements.

Before addressing the diversity of eye movements, we should look at the history of this research tool, to better understand its rational background. The study of eye movements began with Delabarre (1898), who used a mechanical lever attached to the eye. Dodge and Cline (1901) introduced a method of photographing corneal movements which then remained a standard measure of eye movements for fifty years.

Buswell's work (1935) was of great importance in the history of eye-tracking because he was the first to analyze eye movements in subjects watching complex scenes. For Babcock et al (Babcock, Lipps, & Pelz, 2002) "Buswell observed that fixation points are correlated to information contained in the images and those that were pertinent for the subject." A decade later, Brandt (1945), working on eye-tracking, acknowledged that Buswell' "looked at the role played by eye movements in learning strategies." Currently, it is generally accepted that the first person to have studied the relationship between eye movements and cognitive processing was the Russian Alfred Yarbus in 1967 (Hayhoe & Ballard, 2005). Indeed, he was not the first to have studied eye movements, but because of his work, the intrinsic nature of the cognitive processing involved in gaze control was put forward. In his research (Yarbus, 1961, 1967), he attached a mirror to the eye in order to observe eye movements. His approach gave rise to the idea that: "seeing was inextricably linked to a subject's cognitive goals"(Hayhoe & Ballard, 2005, p. 188).

After this first stage, further research mainly used a stationary eye-tracker that immobilized the subject's head. Without realizing it, we move our eyes about three times a minute. This is what we call rapid eye movements or saccades. These eye movements allow us to rapidly orient and then maintain our gaze onto a new fixation point. Several empirical results support the claim that fixations play an essential role in coding information from the environment (J. M. Henderson, 2003; J.M. Henderson, Brockmole, Castelhano, & Mack, 2007; Richardson & Spivey, 2000). Thus the fixations (duration and spatial positions), contribute to information processing.

Henderson defines gaze control as the selection of fixations across a scene in real time, continuously implicating perceptive, cognitive and behavioral activity (J. M. Henderson, 2003). The subject must therefore consider the different elements of his environment in order to direct his gaze. The time spent fixating on an object in a static scene is linked to the probability of remembering that object (Saint-Aubin, Tremblay and Jalbert, (2007). Hence it is important to study not only where subjects fix their gaze, but also the duration of fixation.

The time spent in fixations varies depending on the situation. Hooge, Vlaskamp and Over (2007) demonstrated that the more difficult the task, the longer the duration of the fixations. These authors also showed that, when the duration of the fixation is very short, the image on the retina will be swept away by the next image, even before the complete information coming from the scene is taken into consideration by the visual system. The duration of the fixation can vary between 50 and 700 ms. According to Viviani (1990), there are three stages during a fixation: (1) programming of the saccade, (2) analyzing the image projected onto the fovea and (3) deciding upon the target of the next saccade. The second stage enables the visual system to record information, like a snapshot, whereas spatial processing relies on the integration of the sequence of fixation points. As if the programming of the next saccade was associated to the actual fixation point.

Henderson (2003) revealed that eye movements convey a rich set of information concerning both visual and cognitive processes. Several works (Liversedge & Findlay, 2000; Rayner, 1998; Sereno & Rayner, 2003; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) have found no fixation at uniform or empty elements, thus considered to provide no information for a task. The elements fixated during the longest periods by the subjects were those that gave information that was relevant to the task. In 1935, Buswell already demonstrated that fixations were not distributed randomly, but were systematically related to the pertinent elements of the environment.

In conclusion, we propose it is proposed that not only fixation positions, but also their duration and sequence might reveal both the underlying cognitive processes and the memory representations thus elaborated.

4. Specificity of visual perception in intellectual disability

Disturbed eye movements are commonly observed in many psychiatric illnesses, such as schizophrenia (see Cocchi et al., 2009). Gaze direction is an important social signal and altered control might be linked to impairments in social or cognitive processes as well.

During the exploration of a set of salient objects by people with mild to moderate intellectual disabilities, (ID) Giuliani et al. (2011) studied how eye movements could be related to the detection of spatial changes in the arrangement of objects. The main finding of this work was that people with ID were more likely than control subjects to detect object permutations, both in gazing more frequently at the displaced objects and in declaring the change. ID subject reactions to the addition of a new object were within the control range. However, while they identified a new change in position, they did not notice an object’s disappearance. The correlations between change detection and gaze reorientation frequency suggested that ID people were more affected than control subjects by object salience, which might mean ID subjects have enhanced attention to the permutation. This suggests that the distinction between salience and novelty may lead to a better understanding of how these people adapt to a novel situation. In the present case, gazes addressed to the largest objects might provide some affordance, guaranteeing the object’s attention and consequently a memory of its position.

This evokes the predictability vs reactivity dualism (Bar, 2009; Bressler & Menon, 2010) by which a relational and more abstract representation guides perception (predictability), placing more weight on the whole configuration than on its parts and anticipating a general feature rather than a list of details. In comparison, the reactivity level would be a response to the salience of a local change, i.e., an affordance (Zhang & Patel, 2006). Finally, the perceptual salience is affected by personal, social and emotional biases, which must also be acknowledged as such if one is to account for a salience dimension.

It has been known for a long time that perceptive processing is “non-habitual” in autism and associated with an enhanced visual discrimination (Bertone, Mottron, Jelenic, & Faubert, 2005; Plaisted, O'Riordan, & Baron-Cohen, 1998). These studies led to other works (Simmons et al., 2009) that, in general, revealed abnormalities in the perception of typically non-social stimuli. Yet the perceptive processing in ecologically relevant tasks has never been studied for adults with an intellectual disability.

These works suggest that adults with intellectual disabilities have specific aptitudes in the processing of visual data (Frith, 1989; Happe & Frith, 2006). These authors’ hypotheses concern the focalization on parts and details (Frith & Happe, 1994, p. 122). Other authors (Mottron, Dawson, & Soulieres, 2009) put forward that “*autistic perception is autonomous from higher-level, top-down influences and may involve a one-to-one or veridical mapping process. On this account, hypersensitivity in autism results from an imbalance in inhibitory and excitatory connectivity between local neural networks in sensory regions*” (see also Baron-Cohen, Ashwin, Ashwin, Tavassoli, & Chakrabarti, 2009; Baron-Cohen & Belmonte, 2005; Bertone et al., 2005; O'Riordan & Plaisted, 2001; Rubenstein & Merzenich, 2003). This “autonomy from higher-level influences” might erroneously encourage the interpretation of a lack of higher level processing. This might prevent an understanding - by clinicians - of sophisticated adaptive compensatory strategies. Moreover, despite all the (important) work done in the area of autism or other intellectual disabilities, the effort in understanding the deficits suffered by these patients has been focused mainly on analyzing how they visually explored social stimuli on pictures(Riby & Hancock, 2009; Rose et al., 2013; Wilkinson & Light, 2014) , but not on how they explored and interacted with their environment.

A more detailed analysis of the visual exploration by ID people would at the same time promote an understanding of their adaptive strategies and motivations and also orient remediation methods. Some recent works are concerned with gaze abnormalities in autism, but are mainly looking for specific stimuli (Saitovitch et al., 2013) or consider attention impairment in a general way (Dube & Wilkinson, 2014). Some authors promote the eye tracking research technology to obtain key information « on what elements attract the individual’s attention (and which ones do not), for how long, and in what sequence », but there are, as yet, no systematic attempts (Light & McNaughton, 2014).

5. Cost and benefits of “altered visual strategies”

Recognizing that retinal images are ambiguous, Helmholtz (1962) suggested that perception is an unconscious and automatic process. For Gregory (1980), however, it is an active process that enables one to formulate and test internal ad hoc models coding the structure of the actual environment. Pellicano and Burr (2012) came up with the hypothesis that perception is based on principles of optimal reasoning when faced with uncertainty. These authors considered that perception errors result from optimal automatic calculations accounting for the relevance of the real world. These optimal calculations aim at reducing overall noise and maintaining coherence and continuity. Pellicano and Burr thus suggested that individuals with ASD have larger “a priori” affecting their style of perception. In this paper, we move forward from this preconceived notion to propose a similar feature in intellectual disability.

In particular cases, Bayesian inference - mediating expectations based on the automatically recorded frequency of events - might sacrifice “a priori" expectation to improve precision, and thus reliability. However, the disadvantage of such a perceptual strategy is to increase the perceptive flow (Mamassian, Knill, & Kersten, 1998). This conceptual framework can be adapted to the case of individuals with ID. A Bayesian framework mode would also account for a reduced adaptation performance, where adaptation corresponds to a dynamic process in which nervous-system sensitivity is permanently recalibrated to estimate the characteristics of one's actual environment. As expressed by Kohn (Kohn, 2007): « Adaptation – ubiquitous in perceptual systems – is a rapid form of experience-dependent plasticity, where sensory experience affects the response properties of neurons and, ultimately, perception ». It is generally accepted that adaptation regulates an auto-calibration of the sensory environment (Andrews, 1964; Barlow, 1990). Intellectual disability thus appears to be characterized by a greater dependency with respect to entering sensory signals, which would result in an enhanced initial sensory processing. By the same token, the individual appears less capable of anticipating his sensory environment. These internal constraints could induce an increased “sensory anxiety”, often reported in situations of sensory overload (Pellicano & Burr, 2012; Pellicano & Macrae, 2009; Pellicano, Rhodes, & Calder, 2013). However, in view of the ID subjects’ cognitive difficulties, this increased sensory processing might suffer from insufficient cognitive capacities. Consequently, this might not result in a “quantitative” difference in sensory processing in and of itself, but would also bias the interpretation of entering information by the sensory system.

This requires that we consider the definition of spatial cognition in psychology. English and English (1958) said that: “for a subject, this is about the awareness of one’s position in time and space." Recognition then becomes cognitive because it is mediated by knowing the situation. This kind of system will enable an individual to spatially orient him or herself with respect to the environment. Hart and Moore (1973) defined three types of reference systems: the ego-centric system, the fixed systems and the coordinate systems. This partition reflects the sequential nature of human ontogenetic development, as it has been described by Piaget and collaborators (Piaget, Inhelder, & Szeminska, 1948).

Piaget proposed a model of spatial organization resulting in an empirical analysis of spatial perception. This is a structuralist theory because Piaget thinks that mental structures of a spatial order are constructed and emerge from the assembly of different modules. The constant dialogue between the mental configuration of an organism and the structure of its environment makes it possible to construct a representation of the real world that is as accurate as possible through two essential processes, assimilation and accommodation. Piaget believed that children go through a first phase in which environmental clues are not organized as a whole. Action is constructed with respect to the child’s movements providing a dynamic input of sensory information. This primary dynamic reference system is ego-centric and gibsonian. Then, in the subsequent phase, the child’s position and movements begin to be oriented with respect to fixed elements of the environment. Later, in coordinate reference systems, a reference point will remain independent of the subject’s position. In the process of coordination, the different fixed systems are linked together to form an overall topographical representation. At this point, it becomes a two-dimensional coordinate system that depends on physical clues from the environment.

Thus, on the basis of our work and clinical observations, we think that people with intellectual disabilities are somewhat trapped in a process which gives them an advantage in detecting any kind of topographical modifications even in a large scene. In return, this strategy brings a permanent flow of noticeable sensory information. This represents an increased integration load that exceeds their capacities. Consequently, subjects are more “impressed” by an object’s intrinsic properties or salience, such as size, color and contrast. Giuliani et al. (2011) showed that adults with mild to moderate intellectual disabilities appear to be attracted to large objects and show individual preferences for taking a particular object as a targeted reference point. This element would thus confirm the presence of a coordinate system that remains dependent on physical clues. This view is compatible with a dual model of cognitive mapping (Jacobs & Schenk, 2003), i.e., the integration of two parallel processing mechanisms of spatial cues (bearing and sketch maps) in a supramodal abstract representation, hence a cognitive map. This cognitive tool mediates the capacity for top down spatial processing, i.e., reactivating local views from memory in the absence of ongoing sensory data. This speeds up mental processing and relieves the networks that would be maintained in on line sensory processing.

6. Concluding hypotheses

From the work reviewed above, we can emphasize that in ecologically relevant tasks, vision is intimately linked to the control of voluntary activity. Visual and other systems involved in most activities play distinct and related roles. In order to understand their contribution in organizing behavior, we need to study these systems while they are integrated to one another, rather than separately, as is usually done in neuropsychological tests meant for people experiencing difficulties. As a result, the observation in ecologically relevant contexts of compensatory adaptation in adults with mild to moderate intellectual disabilities allows us to point out specific strategies instead of deficits.

In our view, the specificities of these persons in integrating visual information emphasize two complementary issues when adapting therapeutic approaches aimed at improving life quality**.** On the one hand, a detailed memorization of the real environment permits ID people to integrate perceptive information into a representation including the precise localization of static objects, but not their spatial relation with nearby objects. In other words, this spatial map does not represent “superobjects” or sketches, as might be obtained by the simultaneous chunking of objects perceived as close together. In addition to a reliance on such a static “patchy” map, we propose that the detection of moving objects (or of static objects during exploratory phases) by these same subjects contributes to a primary bearing map. This is a spatial mode of processing separate objects within the framework of an absolute reference system, such as the bearing map in the dual mapping process developed by Jacobs and Schenk (2003). Following this model, a hypothetical “patchy map” would orient and qualify movements, as in a bearing map, with the load that it does not provide “a light and abstract” cognitive map of related places. If not integrated to a sketch map, it might lead to an overflow of active spatial information.

Our clinical experience has brought us to work with these hypotheses. We understood that individuals with ID do not filter incoming information and are consequently overwhelmed by the excess of information not compacted into “superobjects”, be it spatial ones such as an object configuration (Giuliani & al, 2011), or symbolically abstract entities. For daily life, we advise those who take care of these persons to reduce the amount of given information. We also teach ID individuals to seek and create calm and understimulating environments in order to help themselves integrate collected information. We work from the hypothesis that these individuals are over-reactive and vulnerable to basic visual affordances, so we give them the means to control their environment using cognitive-behavioral methods. Finally, we can provide therapeutic help to individuals with ID with the aim of better adapting the perceptual features of the environment. In our approach, visual tracking in daily life plays a prominent role for analyzing subjects' spontaneous adaptive strategy in their environment. From this description, we develop simple and intuitive stratagems to encourage more suitable - but still spontaneous - visual guidance for reeducation. It could be the suggestion that the therapist wears a colored ribbon, or leaves their hair down, or deposits a salient object in a particular position. The reliance on these cues by the subject is easily assessed thanks to continuous eye tracking recording. The difficulty in explicating such processes in a scientific and rigorous manner is that they are based on patients' individual specificities, spontaneous biases (how they explore their environment) and usual environment, but are nevertheless integrated into a theoretical perspective of brain function.

In sum, we have tried to elaborate some initial basics for understanding the structure of altered mechanisms of visual perception and spatial representation in adults with ID, but without autism. Further studies involving a more precise use of this theoretical framework on a larger heterogeneous population with ID are still in progress.

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