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GENETICS AND NEUROSCIENCE (C O'TUATHAIGH, SECTION EDITOR)

The Neural Correlates of Visual Perspective Taking: a Critical Review

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Abstract

Purpose of Review Visual perspective taking (VPT) enables us to understand, anticipate, and interact with other social beings by accurately computing how and what they see in their environment. The present review provides an up-to-date review of the neural mechanisms underpinning VPT that integrates all neuroscientific methods and, importantly, organizes studies based on the distinct cognitive dimensions of VPT they measure.

Recent Findings Recent studies are characterized by a greater use of transcranial stimulation and a more diverse use of contrasts in analyses. Recent findings suggest namely that the temporoparietal junction has multiple roles in VPT and that the dorsal posterior precuneus is neither related to the inferential process nor the decentering process of VPT.

Summary By organizing the findings according the respective cognitive processes tapped into, this review sheds a new light on the neural bases of VPT and advocates for an approach that acknowledges the multidimensionality of VPT.

Keywords Visual perspective taking · Spatial perspective taking · Visuo-spatial · Mentalizing · Cognitive empathy · Neuroimaging

Introduction

From playing hide-and-seek, avoiding bumping into each other in a crowded place, to coordinating a team of movers, we constantly need to take into account what other people see—a cognitive act commonly referred to as visual perspective taking (VPT). A major attempt to decipher the mechanisms underpinning VPT is to investigate its neural bases. To this day, a consistent picture of the neural bases of VPT has been lacking in the current behavioral neuroscience literature. Three obstacles may have caused this: Previous attempts to review neuroscientific studies of VPT (i) focused on a limited number of neuroscientific methods, (ii) were conducted too early to review a sufficient number of studies, and (iii) merged into their analyses studies tapping into distinct cognitive processes. The present review of the neural basis of VPT addresses these issues by reviewing the most up-to-date literature, by integrating studies using transcranial stimulation, neuroimaging, and brain-damaged patients, and by grouping results according to the particular cognitive processes measured.

Organizing studies based on measured cognitive processes necessitates the deconstruction of the cognitive processes underpinning VPT in general, within each task, and within each contrast analysis conducted. This may prove challenging because virtually, all measures of VPT performance provide a single score. This score is systematically obtained by contrasting a performance on an experimental condition versus a control condition. However, researchers have devised different measures and contrasts depending on what particular aspect of VPT they deemed important. Some researchers, particularly in social psychology and psycholinguistics, have focused on the ability to engage and successfully achieve the inhibition of the first-hand experienced self-perspective (i.e., the decentering process) whereas some others, particularly in developmental and cognitive psychology, focused on the ability to create a novel perspective that matches the one actually held by another person (i.e., the inferential process). Hence, some VPT tasks (e.g., Director task [1]) particularly capture the decentering by contrasting an inconsistent (or conflicting, incompatible, and experimental) perspectives condition to a consistent (or shared, compatible, and control) condition while other tasks (e.g., laterality judgments) are better suited to particularly capture the inferential process, such as the

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capacity for mental rotation, by contrasting a 3rd-person-perspective (3PP; or other-perspective, avatar, and altercentric) condition to a 1st-person-perspective (1PP; or self-perspective, control, and egocentric) condition. Critically, previous reviews and meta-analyses failed to acknowledge the diversity of contrasts; they have been analyzed altogether as if VPT were a unidimensional construct. This may be partly due to the scarcity of studies investigating the neural bases of VPT but also to the fact that, until recently, there was no established multidimensional measure of VPT.

We developed a line of research aiming to assess VPT in a multidimensional fashion [2] using to the Dot paradigm as devised by Samson and colleagues [3]. The Dot paradigm orthogonally crosses the consistency factor (consistent vs. inconsistent perspectives) with the perspective factor (self- vs. other-perspective instructions), thus allowing separate measuring of performance on each main effect. The consistency contrast looked at the decentering but, this time, irrespective of the perspective to inhibit. A second particular feature of the Dot paradigm is that the inferential process (i.e., computing the avatar's line of sight) is efficient and thus occurs in all conditions irrespectively of the instructions [3, 4•]. Consequently, the behavioral performance measured by the perspective contrast did not capture the inferential process but rather the relative salience of the information pertaining to self- and other-perspectives. The Dot paradigm allows therefore to capture two sets of cognitive processes forming two dimensions. We have shown that enduring or situational factors influence one dimension but not the other [2, 5, 6•, 7] and that there is a significant amount of inter-individual difference along both dimensions [6•]. These insights bear important implications for the interpretation of the neural bases of VPT. Prior to the brain localization, we should ask ourselves what cognitive processes are captured for each task and each contrast.

The main existing classification of VPT tasks pertain to the inferential process that has to be performed to properly complete the task. Level-1 VPT refers to the computation of another person's line of sight to infer *what* s/he can or cannot see whereas the level-2 VPT refers to the mental transformation (e.g., a rotation) performed to infer *how* a scene or an object is seen from the other person's perspective [8]. A key difference is the lower efficiency of the level-2 inferential process. Depending on the extent of transformation required, the level-2 computation of the other person's perspective can be very effortful. A second classification of the task is what participants are instructed to do with the content of the other person's perspective. In the Dot paradigm, participants need to verify a cued number (0–3) with the number of objects seen by the avatar (0–3); the number never exceeds 4 and the working memory load is minimal (1 digit). In the Director task, however, participants receive a verbal instruction that refers to an object on a shelve ("move the small ball") and need to take into account what objects the Director sees to select the object referred to according to the instructor's perspective. Both tasks require the computation of level-1 visual perspectives but their further processing differ significantly.

To recap, previous reviewing attempts were limited by indistinctively combining VPT studies that measured different cognitive processes underlying VPT. The present review aims to shed a new light on the neural bases of VPT by integrating a large variety of neuroscientific methods and by organizing the findings of studies according to the cognitive processes tapped into by each task and contrast.

Methods

Literature search was conducted on Google Scholar with "visual perspective taking" and "fMRI" since fMRI was expected to be found in any manuscript inspecting the neural correlates of VPT. Publication date was set to start from 2013. Search resulted in 419 entries. Thirteen additional entries came from a meta-analysis conducted in 2013 [9•]. Study inclusion criteria where the use of a method informative about neural correlates (i.e., transcranial direct current stimulation (tDCS), transcranial magnetic stimulation (TMS), localized brain injury patients, evoked-related potential (ERP), functional magnetic resonance imaging (fMRI), magneto-encephalography, positron emission tomography, near-infrared spectroscopy (NIRS), and intracranial cells recording) and the completion of a task instructing to compute the visual perspective of another person by adults. Thirty articles were included (see Table 1), totalizing 35 contrasts of interest. Each experiment was categorized between 3 types of visual perspective computation. The first category ($N = 11$) is objects counting via level-1 VPT, where the number of objects seen by a person is calculated by computing his/her line of the sight (e.g., Dot paradigm). The second category ($N = 12$) is laterality decision via level-2 VPT, where the position of objects from to another person's angle of view is calculated through mental rotation. The third category ($N = 7$) is the instructor-based level-1 VPT, where the selection of an object on a specific instructed location is performed via computation of the instructor's line of sight (e.g., Director task). One remaining study used level-2 VPT to count objects on a specific instructed location in reference to another person's angle of view [31]. Each study was further categorized based on the contrasts performed for each experiment. The first contrast category was the *Consistency for other-perspective* (C-other) that compares the inconsistent versus the consistent perspectives conditions ($N = 12$). Two studies reported effects on the consistency factor on self-perspective trials but their analysis is beyond the scope of this review [12••, 19•]. The second contrast is the *main effect of Consistency* (C-main; $N = 4$), that is, irrespective of

Table 1 Summary description of studies included in the review

Study	Method	DV	VPT type	Contrasts
McCleery et al. [10•]	ERP	Latency, amplitude	Level-1 counting	C-main, P-explicit
Meurrens et al. [11]	tDCS on r IFG	IES	Level-1 counting	C-main
Ramsey et al. [4•]	fMRI	BOLD	Level-1 counting	C-main, C-other
Schurz et al. [12••]	fMRI	BOLD	Level-1 counting	C-main, C-other
Soutschek et al. [13]	rTMS on pTPJ	Accuracy	Level-1 counting	C-other
Beck et al. [14••]	FPVS-ERP	Amplitude	Level-1 counting	C-other
Santiesteban et al. [15•]	rTMS on rTPJ	RT	Level-1 counting	P-explicit
Schnell et al. [16]	fMRI	BOLD	Level-1 counting	P-explicit
Vogeley et al. [17]	fMRI	BOLD	Level-1 counting	P-explicit
Kaiser et al. [18]	fMRI	BOLD	Level-1 counting	P-explicit
Martin et al. [19•]	tDCS on dmPFC	RT	Level-1 counting Level-2 laterality	C-self
Sulpizio et al. [20]	fMRI	BOLD	Level-2 laterality[1]	C-other, P-explicit
van Elk et al. [21•]	tDCS on rTPJ	RT	Level-2 laterality	C-other, P-explicit
Blanke et al. [22]	TMS on rTPJ	RT	Level-2 laterality	P-full
Kockler et al. [23]	fMRI	BOLD	Level-2 laterality	P-full
Meng et al. [24]	fNIRS on dlPFC	Coxy-Hb	Level-2 laterality	P-full
Conson et al. [25]	tDCS on dlPFC	RT, allocentrism	Level-2 laterality	P-full
Mazzarella et al. [26]	fMRI	BOLD	Level-2 laterality	P-full
David et al. [27]	fMRI	BOLD	Level-2 laterality	P-full
David et al. [28]	fMRI	BOLD	Level-2 laterality	P-full
Aichhorn et al. [29]	fMRI	BOLD	Level-2 laterality[2]	P-full
Agarwal et al. [30]	fMRI	BOLD	Level-2 laterality[3]	P-full
Besharati et al. [31]	Brain-lesion	Accuracy	Level-2 counting	P-explicit
Eack et al. [32]	fMRI	BOLD	Level-1 Instructor	P-full
Vanlangendonck [33]	fMRI	BOLD	Level-1 Instructor	C-other
Eack et al. [34]	fMRI	BOLD	Level-1 Instructor	C-other
Dumontheil et al. [35]	fMRI	BOLD	Level-1 Instructor	C-other
Santiesteban et al. [36]	tDCS on r TPJ	Accuracy	Level-1 Instructor	C-other
Santiesteban et al. [37•]	tDCS on r/l TPJ	Accuracy	Level-1 Instructor	C-other
Nobusako et al. [38]	tDCS on r TPJ, r IFG	RT, accuracy	Level-1 Instructor	C-other

IES inverse efficiency score, *BOLD* blood-oxygen-level dependent, *FPVS* fast periodic visual stimulation, *coxy-Hb* content of oxygenated hemoglobin

[1] Instructed to study objects positions from avatar/self-perspective to later detect changes in a changed angle of view

[2] Front/behind instead of left/right judgments

[3] Instructed to study objects positions from avatar/self-perspective to later detect changes in a changed angle of view

perspective (other- or self-perspective). The third contrast is the *explicit Perspective* (P-explicit; $N = 8$) contrast; it includes conditions where participants are explicitly instructed to take the other- or self-perspective. Importantly, this contrast includes only tasks where the other person's visual perspective is computed in both other- and self-perspective condition. The fourth contrast is *full Perspective* (P-full; $N = 10$) contrast comparing the other- versus self-perspective, in which the other person's visual perspective is computed only in the other-perspective condition and is inconsistent with self-perspective. Findings pertaining to each contrast are reviewed separately, with a closer look at the task type present in each contrast. The cognitive processes tapped into by each contrast are discussed in the following sections.

Results

Main Consistency Contrast (C-Main)

For the main effect of the inconsistent > consistent contrast (i.e., irrespective of the perspective taken), an EEG study [10•] reported the modulation by consistency on a late ERP component corresponding to the right inferior frontal gyrus (IFG). A tDCS study [11] reported an increased consistency effect following cathodal (inhibitory) stimulation of the anterior IFG location (F8 scalp location). An fMRI study [4•] reported the right IFG but a more dorsal and posterior location extending into the middle frontal gyrus (MFG; Brodmann area (BA) 9). The right IFG was however not reported in a fMRI using the same Dot paradigm as the 3 previously mentioned studies [12••] but, interestingly, it differed only in having blocked self- and other-perspective trials. Blocking perspective trials (instead of mixing them) have been shown to significantly reduce the consistency effect at behavioral level (e.g., [3]). Both fMRI studies reported the right posterior IPS extending into the lateral superior occipital cortex.

Consistency Contrast for Other-Perspective (C-Other)

For the consistency contrast limited to conditions where participants took the other person's perspective (inconsistent/other > consistent/other), 7 fMRI studies were conducted, from which the bilateral dorsal lateral PFC (dlPFC) is most commonly reported (e.g., [34]). A novel ERP paradigm using fast visual presentations further confirmed the recruitment of the right dlPFC [14••]. The posterior frontal cortex was reported at level of MFG (BA 6, 9) bilaterally [4•, 20, 32, 33], and more dorsally in left hemisphere [12••]. Congruently, anodal stimulation on FC6 scalp position (i.e., posterior mid/inferior BA 9) reduced the consistency effect [38]. The posterior IPS is reported twice bilaterally [4•, 12••] and once on left [20] and the right hemisphere [33]. The latter activations extend in the angular gyrus, whose ventral part is often referred to as the temporoparietal junction (TPJ) [39]. The posterior TPJ mainly encompasses the angular gyrus and has been reported bilaterally [4•], on the left hemisphere [12••, 20, 32] and the right one [33]. Congruently, three tDCS studies have applied anodal (i.e., excitatory) stimulation on the TPJ (3 right TPJ, one left) and all reported a reduced Consistency effect [36, 37•, 38]. Congruently, an rTMS study disrupted the right posterior TPJ and found an increased consistency effect [13]. The posterior inferior temporal cortex (fusiform and lingual) is regularly reported bilaterally [4•, 12••] or solely on the right hemisphere [20, 33]. In addition, nearby superior cerebellum activations were reported twice [12••, 33] and the dorsal occipitotemporal areas were reported twice bilaterally [12••, 20]. Finally, there was a triple report of the posterior dorsal precuneus (dpPC) [12••, 20, 33] and the posterior dorsomedial PFC (dmPFC) [32, 33, 35].

Explicit Perspective Contrast (P-Explicit)

The explicit perspective contrast is the comparison between the other-perspective and self-perspective instruction conditions (Other > Self) irrespective of the consistency between perspectives. Importantly, however, this contrast is suited only for tasks where it can be expected that the other person's perspective is also computed in self-perspective trials, which is only the Dot paradigm because its level-1 inferential process and the dot counting are highly efficient. Hence, the computation of the other person's perspective and decentering are both canceled out by the contrast, leaving out whatever is more active for the explicit perspective computation of the other person's perspective than those of the self-perspective (where the other-perspective is only implicitly computed). Four fMRI studies [4•, 16–18] inspected this contrast; 3 reported the dorsal posterior precuneus [16–18]. Interestingly, the one fMRI that did not report the precuneus is the sole study showing no performance advantage for the self-perspective. Moreover, Vogeley and colleagues [17] have shown that dpPC is actually more activated than baseline both in self- and other-perspective conditions, but to a significantly higher extent in the other-perspective condition. Congruently, another fMRI study however tapping into level-2 VPT [30], with conditions where similar mental rotation is performed in the other- and self-perspective conditions, reported dpPC activation in both conditions (> baseline); both fMRI activation and behavioral performance were not different between self- and other-perspective. An ERP study with a performance self-perspective advantage [10•] has reported later latencies of amplitude for the other-perspective bilaterally over the parietal cortex that could have reflected modulation in the dpPC but also in the bilateral anterior TPJ (supramarginal and posterior superior temporal sulcus). This latter finding is in line with a rTMS study that disrupted the right anterior TPJ [15•] and observed a *reduction* of the self-perspective advantage in the Dot paradigm.

Full Perspective Contrast (P-Full)

Ten studies have compared a condition where participants are instructed to adopt another person's perspective with a condition where they adopt their own-eyes egocentric perspective. The other-person perspective is inconsistent with the self-perspective and is most often based on level-2 VPT, which require mental rotation as the inferential process. Because the self-perspective computation does not require mental rotation and the other person's perspective is not salient enough to interfere with self-perspective performance, this contrast captures both the decentering from the self-perspective and the level-2 inferential process. The five fMRI studies consistently reported the posterior MFG (BA 6 and BA 9) extending into the premotor IFG and SFG either bilaterally [23, 27, 29, 40] or only in the left hemisphere [26]. Congruently, a group of patients (diagnosed with hemiplegia and anosognosia), that differed from another group of patients (diagnosed with hemiplegia only) by their distinctive brain damage location in right posterior MFG (extending into anterior insula and superior premotor cortex), showed significantly lower performance on other-perspective trials only [31]. In addition, the IPS was found twice bilaterally and thrice in the left hemisphere with a systematic extension into the dorsal posterior supramarginal gyrus (i.e., anterior TPJ). Intriguingly, however, anodal (i.e., excitatory) tDCS on the same right anterior TPJ slowed down the task performance in the other-perspective condition [21•]. In contrast, disruptive TMS applied on a more ventral right TPJ location slowed down performance in the other-perspective condition [22]; the TMS location was first identified in an EEG experiment that reported bilateral ventral TPJ. The posterior inferior visual cortex was reported trice [23, 28, 29] and nearby superior cerebellum (either lateral, medial, or both) was reported in four studies. Two fMRI studies reported strikingly similar results: bilateral anterior insula, posterior dmPFC, bilateral IPS, bilateral posterior MFG (BA 9, 6) extending into dorsal premotor, and dpPC [23, 28]. These two studies differ from others in that they include conditions where VPT judgements are being applied to moving objects. Finally, a fNIRS study targeted on the anterior dlPFC reported higher activation for the other-perspective condition [24] while cathodal tDCS applied on a more posterior left dlPFC (or anodal on right dlPFC) reduced performance in the other-perspective condition [25].

Discussion

This review aimed at bringing a new light to the neural bases of VPT by integrating the most up-to-date findings derived from all neuroscientific methods and by organizing them according to the contrasts used and their underlying cognitive processes. First, overall—across all contrasts—the review revealed the regular involvement of the dlPFC, the posterior MFG extending into lateral premotor cortex, the IFG, the dpPC, the TPJ, the IPS, the inferior posterior temporal cortex, and superior cerebellum. The anterior dmPFC, an area typically associated with mentalizing, was inconsistently reported across studies and in locations. These results are in line with the most recent meta-analysis performed [9•], that also noted the absence of anterior dmPFC in VPT. Unlike this review the authors additionally reported the right insula and the posterior middle temporal gyrus (between TPJ and precuneus). These two areas however present the weakest meta-analytic value, which indicates they present the weakest overlap across studies. In addition, the dlPFC was not reported in the 2013 meta-analysis because the dlPFC was mainly reported by 7 recent studies.

The decentering, that is the handling of conflict (or interferences) between the self- and other-perspectives, is tapped in 3 reviewed contrasts: the main consistency, the consistency specific to the other person's perspective, and the full Perspective contrasts. These three contrasts share the recruitment of the posterior MFG. This area encompasses the frontal eye field (FEF), inferior FEF (iFEF), the inferior frontal junction (IFJ), and the posterior part of the dlPFC. While the FEF and iFEF are involved in oculomotor control and spatial attention, the posterior dlPFC and IFJ are involved in cognitive control and particularly in conflict resolution such as the one elicited by the inconsistent > consistent contrast of the Stroop task [41]. Decentering in VPT clearly taps into domain-general conflict resolution but might as well involve oculomotor-derived visuo-spatial attention. In particular, correct performance on inconsistent perspectives trials in level-1 VPT requires to resist the gaze-cued shift in spatial attention triggered by the avatar orientation. Congruently, the report of the posterior MFG is frequently accompanied by the report of the posterior IPS, which is involved in visual attention and control of eye movements. The posterior MFG and the IPS form a functionally connected network (as observed on neurosynth.org, [42]) that also includes the anterior IFG extending into the anterior insula, the more anterior lateral PFC, and the posterior dmPFC, three areas that have been regularly reported as well. This whole network is known as the task-positive network and reflects the higher-demand on cognitive control. Interestingly, this network was not reported in the explicit perspective (other vs. self) contrast in which we can reasonably expect that the decentering process is canceled out.

The contrast of explicit perspective (other > self) is harder to interpret since it supposedly cancels out both the inferential process and the decentering. One interpretation is that it captures a more goal-directed (i.e., explicitly instructed) visual experience than the passive first-hand egocentric experience. A somewhat alternative interpretation is that it would reflect the difference between the explicit and implicit computation of the other person's perspective, where only the former yields a conscious experience of what and how the other person sees. This contrast, although still poorly reported, indicates the involvement of the dcPC while the TPJ's involvement is more ambiguous (supported only by one ERT study and a TMS study). Unlike other parts of the precuneus involved in sensorimotor and affective processing, the dcPC is particularly involved in high-level cognitive functions and high-level visual processing [43]. The exact function of this area is still debated but its involvement in mental imagery, episodic memory retrieval, voluntary shifts in visual attention, and consciousness suggests it might underpin an active, voluntary, conscious, and probably effortful construction of a self-experienced percept, including transforming an egocentric frame of reference into a third person's perspective [44]. The function of the precuneus in active goal-directed self-experience is congruent with the observation that the dcPC can be found in both the self-perspective and other-perspective condition and that its higher activation in the other-perspective condition seems conditioned to the presence of a significant performance self-perspective advantage or a more difficult perspective taking in the other-perspective condition.

The inferential process in VPT, that is the particular mentalizing process allowing to compute what or how another person sees, is hard to isolate via a contrast: It is likely to be either canceled out (inconsistent other > consistent other, or other > self when inferential process is efficient) or confounded with decentering (other > self in full perspective). Hence, the neural correlates can only be indirectly inferred by subtracting the brain areas that were consistently reported across the 3 contrasts that tapped into decentering from the results of the full perspective. This subtraction leaves the inferior temporal cortices and the nearby superior cerebellum. An apparent contradiction is that these two areas were also regularly reported for the consistency for other-perspective contrast. However, it is actually expected that the top-down selection of the other-perspective over the self-perspective strengthens the posterior temporal areas sustaining the inferential process, especially since fMRI activation reflects mainly post-synaptic activity. While it is highly plausible that the posterior temporal areas contribute to the inferential process, the role of the cerebellum is less clear. Reports of the cerebellum are localized in the dorsal posterior (medial and lateral) areas, which corresponds to cognitive functioning and overlaps most strongly with a locus of activity during mental rotation tasks (in comparison with working memory, language, affective and sensorimotor tasks) [45, 46]. Although the cerebellum is not expected to host representations, it may store complex mental internal models that indirectly inform about when an operation was successfully carried or not [47]. However, the cerebellar activity was not reported only in level-2 VPT and may thus reflect more domain-general executive processes.

Special attention must be given to the TPJ because it has been reported at least once across all contrasts, including in the main effect of consistency contrast, in Ramsey and colleagues [4•]. This confirms the TPJ's variety of cognitive functions and the lack of benchmarks to delineate what belongs to the TPJ and how it can be subdivided [39]. However, some researchers have proposed an overarching function of TPJ. For instance, it may be in charge of representing the social context by integrating social, spatial, and body perceptions [48], detecting breaches of internal model expectations such as incongruence, or conflict, between self-perspective and another person's perspective or between proprioceptive and visual inputs during multisensory integration forming the egocentric body frame of reference [49, 50]. We have recently proposed that the TPJ‘s role in social cognition relates to self-other distinction by enabling the detection self-other incongruences [51]. This latter interpretation could explain why excitatory tDCS stimulation of the TPJ reduces the consistency effect [36, 37•, 38] while disruptive tDCS stimulation of the TPJ increases the consistency effect [13]. In the same vein, a TMS study [22] showed a specific disruption of performance at taking an avatar's level-2 visual perspective when disrupting the right ventral TPJ specifically within the same time window as identified by McCleery and colleagues [10•]; the latter study reported a significant perspective effect (other > self) on the identical location. Finally, the results of two recent studies seem to jeopardize the validity of the aforementioned overarching interpretations of the TPJ activity by reporting that disruptive rTMS on right TPJ reduced the self-perspective advantage in VPT performance [15•] while excitatory tDCS on right TPJ impaired the computation of another person's perspective [21•]. A good understanding of the TPJ will be reached only with a systematic fined-grained functional mapping of TPJ that takes into account which perspective and which VPT strategy participants actually used. For instance, the processing of another person's gaze is particularly relevant to VPT and is located in the posterior superior temporal sulcus [52], the ventral part of the right TPJ, while a slightly more dorsal location of the TPJ is commonly associated with conflict resolution and violations of expectations [39].

Conclusion

Reviews and meta-analyses are designed to only look at consistencies across studies. If the tasks and contrasts are heterogeneous and analyzed altogether, the consistent findings are likely to be limited to domain-general processes merely reflecting task difficulty. An accurate picture of the neural bases of VPT is only within sight by acknowledging this heterogeneity and the multidimensionality of VPT. This review was a first attempt to highlight the variety of contrasts and the underlying cognitive processes that any researcher needs to consider when designing future experiments or interpreting previous findings.

Organizing the findings according to the contrasts performed has yielded new looks on particular VPT-related areas such as the dorsal posterior cerebellum, the TPJ, and the dpPC. As expected, the most consistently reported areas remain those mainly recruited by domain-general processes. The failure to find adequate consistency in posterior representational areas may be explained by the diversity in the inferential processes, in their further instructions-based processing, in the particular task settings (visual appearances, timing, social context [53], or the dynamic nature of stimuli [23]), and in the cognitive strategies actually performed by the participants [54•]. Fortunately, solutions for future studies are available: favoring tasks that allow multiple contrasts (e.g., [10•]), designing several and novel control conditions (e.g., [12••, 33]), or exploiting behavioral performance (e.g., [24]) and self-reports (e.g., [18]) to homogenize participants' performance and personalities [6•].

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Compliance with Ethical Standards

Conflict of Interest The author declares that there are no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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