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Time pressure disrupts level-2, but not level-1, visual perspective calculation: A process-dissociation analysis

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ABSTRACT

Reasoning about other people's mental states has long been assumed to require active deliberation. Yet, evidence from indirect measures suggests that adults and children commonly display behavior indicative of having incidentally calculated both *what* other agents see (level-1 perspective taking) and *how* they see it (level-2 perspective taking). Here, we investigated the efficiency of such perspective calculation in adults. In four experiments using indirect measures of visual perspective taking, we imposed time pressure to constrain processing opportunity, and we used process-dissociation analyses to isolate perspective calculation as the process of focal interest. Results revealed that time pressure weakened level-2, but not level-1, perspective calculation—a pattern that was not evident in error-rate analyses. These findings suggest that perspective calculation may operate more efficiently in level-1 than in level-2 perspective taking. They also highlight the utility of the process-dissociation framework for unmasking processes that otherwise may go under-detected in behavior-level analyses.

1. Introduction

Effectively managing the challenges and opportunities of social life necessitates reasoning about what other people see, know, and want. This capacity for mentalizing, or perspective taking, is essential for explaining others' actions and for predicting what they might say or do next. Although it has traditionally been assumed that successfully recognizing another agent's divergent view of the world requires active and effortful deliberation, demonstrations of so-called "implicit mentalizing" in adults, children, and even infants suggest otherwise (for reviews, see Baillargeon, Scott, & He, 2010; Schneider, Slaughter, & Dux, 2015; Schneider, Slaughter, & Dux, 2017; Scott & Baillargeon, 2017; but see Kulke, von Duhn, Schneider, & Rakoczy, 2018). For example, multiple studies have reported evidence that people display behavior on indirect measures indicative of having incidentally calculated both *whether* an object is or is not visible to another person—level-1 perspective taking (Flavell, Everett, Croft, & Flavell, 1981)—and *how* that object appears (i.e., the object's identity) to the other person—level-2 perspective taking (Flavell et al., 1981)—in the absence of deliberately attempting to do so (e.g., Elekes, Varga, & Király, 2016; Elekes, Varga, & Király, 2017; Qureshi, Apperly, & Samson, 2010; Samson, Apperly, Braithwaite, Andrews, & Bodley Scott, 2010; Surtees & Apperly, 2012; Surtees, Apperly, & Samson, 2016; Surtees, Samson, & Apperly, 2016).

Here, we examine the efficiency (i.e., dependence on processing resources or lack thereof; Bargh, 1994) of such incidental perspective calculation in healthy adults. Specifically, we ask whether constraining processing opportunity by imposing time pressure—a common research strategy for probing the efficiency of cognitive processes (Bargh & Thein, 1985; Sherman, Krieglmeyer, & Calanchini, 2014)—impedes the calculation of other agents' perspectives in indirect measures of level-1 and level-2 visual perspective taking.

2. Indirectly measuring level-1 and level-2 visual perspective taking

Ascribing mental states to oneself and others is thought to involve several distinct cognitive processes. On one view, these processes include *calculating* possible mental contents (e.g., what another person sees, knows, or wants) and *selecting* the most plausible among these potential contents while simultaneously *inhibiting* competing content (Leslie, Friedman, & German, 2004). Most *direct* measures of perspective taking (e.g., standard false-belief tasks; Wimmer & Perner, 1983) conflate these processes by requiring that people explicitly report their inferences about others' mental states while simultaneously inhibiting their own mental states (Ramsey, Hansen, Apperly, & Samson, 2013). With the advent of *indirect* measures that monitor eye gaze and other

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incidental behaviors that do not require deliberate reporting (see Schneider et al., 2015, 2017, for examples of such measures), however, assessing perspective calculation independent of perspective selection may now be possible.

In one such indirect measure of level-1 visual perspective taking (hereafter, L1-VPT), participants view a room containing a human avatar and a varying number of objects (Samson et al., 2010). On some trials, the avatar can see the same number of objects participants themselves can see (i.e., consistent trials); on other trials, the avatar cannot see some of the objects that are visible to participants (i.e., inconsistent trials). A robust *altercentric-interference* effect commonly emerges in this task wherein participants have more difficulty—operationalized as slower response times and/or more errors—reporting how many objects they themselves can see when their own perspective and the avatar's perspective are in conflict versus when self and avatar perspectives are in unison (e.g., Qureshi et al., 2010; Samson et al., 2010; Surtees & Apperly, 2012). Because participants' focal goal in this task is simply to report how many objects are visible to themselves, any incidental processing of the avatar's perspective should interfere with this objective. For this reason, altercentric-interference effects in indirect measures of L1-VPT have frequently been interpreted as reflecting the spontaneous calculation, or computation, of *what* the avatar can see (e.g., Ramsey et al., 2013; Samson et al., 2010; Todd & Simpson, 2016).

Surtees, Samson, et al. (2016) developed an indirect measure of level-2 visual perspective taking (hereafter, L2-VPT) that is structurally similar to the L1-VPT task but differs in terms of its visual content. In this task, participants view a room containing a human avatar and a numeral (6 or 9) sitting on a table. On consistent trials, the numeral is standing upright on the table and thus looks identical to the avatar and participants (e.g., both see a 6); on inconsistent trials, the numeral is lying flat on the table and thus looks different from the two perspectives (e.g., participants see a 6, but the avatar sees a 9). Altercentric-interference effects have also been reported for this L2-VPT task. Here, participants have more difficulty reporting the numeral's identity from their own perspective when it has a different identity from the avatar's perspective (Elekes et al., 2016, 2017; Surtees, Apperly, et al., 2016; Surtees, Samson, et al., 2016; but see Surtees, Butterfill, & Apperly, 2012). Because participants' focal task goal is simply to report the numeral's identity from their own perspective,[1] any incidental processing of the avatar's perspective should interfere with this objective. Thus, altercentric-interference effects in indirect measures of L2-VPT have been interpreted as reflecting the spontaneous calculation of the *way* something looks to the avatar (e.g., Elekes et al., 2016, 2017).

One problem with interpreting altercentric-interference effects in this way, however, is that it assumes altercentric interference provides a "process-pure" index of visual perspective calculation (Payne, 2005; Sherman et al., 2014). By equating a behavioral effect (altercentric interference) on an indirect measure (self trials in the L1-VPT and L2-VPT tasks) with the process of focal interest (perspective calculation), this approach—sometimes called the "task-dissociation" approach (Payne, 2001)—ignores (*i*) the fact that multiple processes may contribute to altercentric-interference effects and (*ii*) the possibility that these processes may have opposing effects on task performance. For example, the presence of altercentric interference as a behavioral effect could indicate high sensitivity to the avatar's conflicting perspective, low ability to report one's own perspective, or both. The absence of altercentric interference could likewise result from a combination of processes (e.g., moderate sensitivity to the avatar's conflicting perspective coupled with high ability to detect one's own perspective). In the latter case of muted altercentric interference, there may be meaningful variability in sensitivity to the avatar's perspective at the process level, but this variability in perspective calculation would be overshadowed at the behavior level by high ability to detect one's own perspective. Claims about perspective calculation, therefore, require isolating this process and estimating its contributions to task performance. Isolating perspective calculation as the process of focal interest in indirect measures of visual perspective taking also affords more precise empirical tests of theoretical claims about the efficiency (or lack thereof) of perspective calculation in these tasks.

[1] Some variants of the L1-VPT and L2-VPT tasks, including those used in the current work, also contain avatar trials in which participants' objective is to respond from the avatar's perspective. Because the avatar trials are less relevant than the self trials for claims about incidental perspective calculation, we restrict our discussion and analyses to the self trials. For the sake of completeness, we report analyses of the avatar trials in the Supplementary Material.

3. Using process dissociation to isolate perspective calculation

The process-dissociation procedure (PDP; Jacoby, 1991) is a well-established analytical technique for quantifying component processes in a single behavioral task, thereby overcoming problems inherent to the "task-dissociation" approach. The PDP framework stipulates *a priori* how these processes interact to drive task performance; it uses behavior on the task to estimate the probability of each process operating. Although the PDP was initially developed to estimate processes that interact to shape performance on memory tasks (Jacoby, 1991; Jacoby, Toth, & Yonelinas, 1993), one of its primary strengths is its applicability across multiple content domains. Indeed, variants of the PDP have been used to estimate processes underlying task behavior in a diversity of content areas, including attitude formation (Hütter, Sweldens, Stahl, Unkelbach, & Klauer, 2012), attributional inference (McCarthy & Skowronski, 2011), decision-making under uncertainty (Ferreira, Garcia-Marques, Sherman, & Sherman, 2006), empathy for pain (Cameron, Spring, & Todd, 2017), moral judgment (Cameron, Payne, Sinnott-Armstrong, Scheffer, & Inzlicht, 2017; Conway & Gawronski, 2013), and racial stereotyping (Krieglmeyer & Sherman, 2012; Payne, 2001). More germane to the current work, the PDP has also been used to elucidate processes underlying altercentric-interference effects in visual perspective taking (Todd, Cameron, & Simpson, 2017).

An important starting assumption of the PDP framework is that component processes underlying task performance can be dissociated by creating conditions that place these processes both in concert and in opposition (Jacoby, 1991; Payne, 2001). Applying the logic of this framework to altercentric-interference effects in visual perspective taking, in conditions wherein one's own perspective and the avatar's perspective are aligned (i.e., consistent trials), directly reporting one's own perspective (i.e., self-perspective *detection*) and incidentally encoding the avatar's perspective (i.e., avatar-perspective *calculation*[2]) lead to the same behavioral response.

The probability of responding correctly on consistent trials equals the probability of reporting one's own perspective (detection) plus the probability of tracking the avatar's perspective (calculation) when detection fails (1 − detection):

$$p(\text{correct}|\text{consistent trials}) = \text{detection} + [\text{calculation} \times (1 - \text{detection})] \quad (1)$$

[2] Todd et al. (2017) used the labels "controlled" processing and "automatic" processing, respectively, for these same process parameters. Such labels are problematic because they conflate *operating principles*, or definitions of what each process is doing (i.e., "detecting" one's own perspective, "calculating" the avatar's perspective), with *operating conditions*, or empirical claims about when each process operates (e.g., Does the process of calculating the avatar's perspective operate when processing opportunity is limited?). Examining whether these processes are characterized by a specific operating condition, resource efficiency, was the focus of the current work. Thus, we use parameter labels reflecting operating principles (for in-depth discussion on operating principles versus operating conditions, see Gawronski & Bodenhausen, 2014; Sherman et al., 2014).

In conditions wherein one's own perspective and the avatar's perspective are misaligned (i.e., inconsistent trials), however, incidentally tracking the avatar's perspective and directly reporting one's own perspective lead to different behavioral responses. The probability of responding incorrectly on inconsistent trials is equal to the probability of encoding the avatar's perspective (calculation) when detection fails (1 − detection):

$$p(\text{incorrect}|\text{inconsistent trials}) = \text{calculation} \times (1 - \text{detection}) \quad (2)$$

With these two equations, one can solve algebraically for separate estimates of self-perspective detection and avatar-perspective calculation:

$$\text{Detection} = p(\text{correct}|\text{consistent trials}) - p(\text{incorrect}|\text{inconsistent trials}) \quad (3)$$

$$\text{Calculation} = p(\text{incorrect}|\text{inconsistent trials})/(1 - \text{detection}) \quad (4)$$

Thus, according to the PDP framework as it is applied here, self-perspective detection reflects the ability to accurately identify whether the numerical content cue matches the visual content in the room from one's own perspective. Avatar-perspective calculation, by contrast, reflects the biasing influence of having incidentally encoded the avatar's perspective, despite having a specific task goal of simply reporting one's own perspective. Fig. 1 displays a processing tree depicting the underlying component processes that lead to correct and incorrect responses on consistent and inconsistent trials in the visual perspective-taking tasks.

Following Todd et al. (2017), we suggest that avatar-perspective calculation is the parameter of focal interest in research that treats altercentric interference as a proxy for "implicit mentalizing" in indirect measures of visual perspective taking (see also Qureshi & Monk, 2018). Todd et al. (2017) recently validated the meaning of this process parameter by demonstrating that it is sensitive to whether the entity in the room is actually capable of seeing. Specifically, they found that perspective calculation was stronger when the entity in the room had agency (i.e., a human avatar) than when the entity did not have agency (i.e., a dual-colored block).

4. The efficiency of perspective calculation

We used the PDP here to isolate perspective calculation as the process of focal interest in the L1-VPT and L2-VPT tasks, and we examined the efficiency of this process by constraining processing opportunity via time pressure. Specifically, we imposed a short response deadline in some conditions, thereby limiting the amount of attentional resources that could be devoted to the tasks (Sherman et al., 2014). Time pressure is a common method for inducing cognitive load; it has been used to investigate the efficiency (or lack thereof) of cognitive processes underlying various psychological phenomena, including moral judgment (e.g., Cameron, Payne, et al., 2017; Suter & Hertwig, 2011), stereotyping (e.g., Kruglanski & Freund, 1983; Payne, Lambert, & Jacoby, 2002), empathy for pain (e.g., Cameron, Spring, et al., 2017), and, importantly, perspective taking (e.g., Epley, Keysar, Van Boven, & Gilovich, 2004; Horton & Keysar, 1996).

How might time pressure affect perspective calculation in L1-VPT and L2-VPT? According to the "two-system" account of mentalizing (Apperly & Butterfill, 2009; Butterfill & Apperly, 2013; Low, Apperly, Butterfill, & Rakoczy, 2016), calculating *what* another agent sees (L1-VPT) is an efficient process that should operate even under conditions of limited processing opportunity. Results from several studies align with this view. For example, Qureshi et al. (2010) found that concurrently performing a resource-consuming motor-inhibition task had no effect on altercentric-interference effects in an indirect measure of L1-VPT, thus providing tentative evidence for the efficiency of perspective calculation. More important, however, a PDP re-analysis of Qureshi et al.'s (2010) data further revealed that performing the secondary task reduced self-perspective detection, but it had no effect on the focal process of avatar-perspective calculation (Qureshi & Monk, 2018), again suggesting that perspective calculation may operate efficiently in L1-VPT. Of most relevance to the current work, Todd et al. (2017), using the same L1-VPT task as Qureshi et al. (2010), found that imposing time pressure with a response-deadline manipulation—the same one used in the experiments reported here—reduced self-perspective detection but had no effect on avatar-perspective calculation, which once again points to the efficiency of the perspective-calculation process in L1-VPT.

Although findings from these studies provide preliminary support for predictions by the two-system account regarding the efficiency of perspective calculation in L1-VPT, Qureshi and Monk (2018) reported another study with contradictory results. Specifically, they found that concurrently performing a resource-consuming working-memory task reduced estimates of both self-perspective detection and avatar-perspective calculation on an indirect measure of L1-VPT. These results,

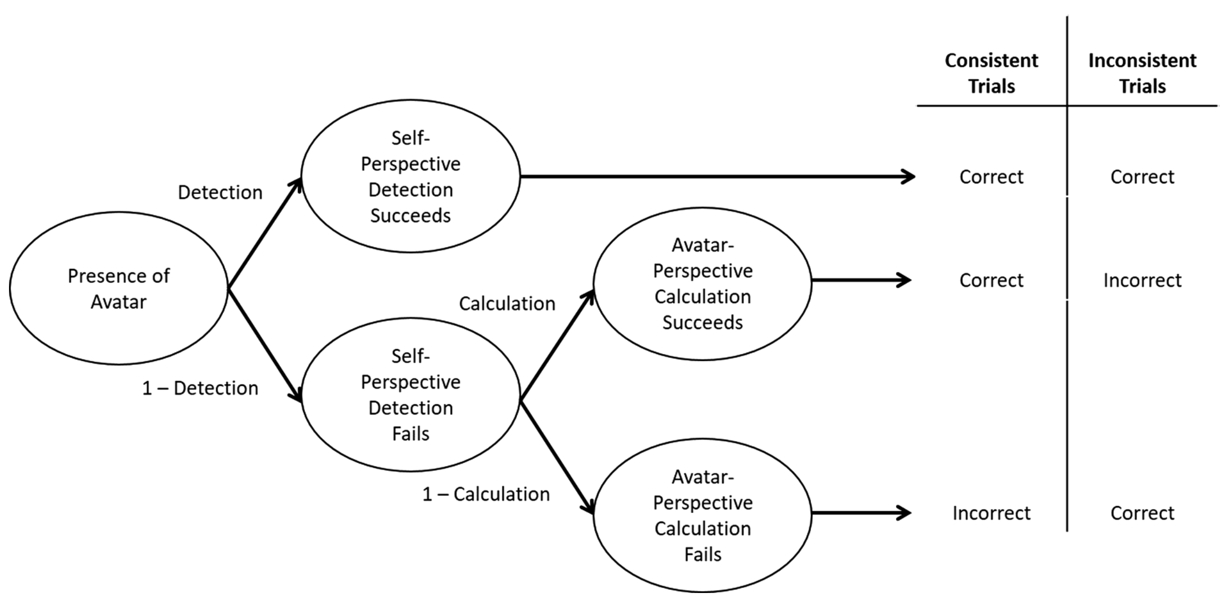

Fig. 1. Processing tree depicting the underlying component processes leading to correct and incorrect responses on consistent and inconsistent trials in the visual perspective-taking tasks.

though inconsistent with the two-system view, do align with an alternative, "one-system" view (Carruthers, 2016, 2017). On this account, the distinction between encoding *what* the person sees (in the L1-VPT task) and encoding *how* the person sees it (in the L2-VPT task) is meaningless because the same concept of "seeing" applies to both tasks equally. Accordingly, this account proposes that any factor that places additional processing demands on perceivers—be it one that is endogenous to the perspective-taking task at hand (e.g., the necessity of an effortful form of embodied mental rotation in L2-VPT tasks; Kessler & Rutherford, 2010; Kessler & Thomson, 2010; Surtees, Apperly, & Samson, 2013a, 2013b) or one that is exogenous to the specific perspective-taking task (e.g., an externally-imposed cognitive load)—-should impede the calculation of another person's visual perspective.

Because much of the existing data on the efficiency of perspective calculation in indirect measures of L1-VPT supports the two-system view, we tentatively predicted that time pressure would have negligible effects on estimates of avatar-perspective calculation in L1-VPT, despite reducing estimates of self-perspective detection. To our knowledge, no prior research has examined the efficiency of perspective calculation in indirect measures of L2-VPT. Both accounts claim, albeit for different reasons, that perspective calculation in L2-VPT is resource-dependent. The two-system account proposes that L2-VPT has signature limits (e.g., dependence on processing opportunity) that do not apply to L1-VPT. On this view, "reasoning about perception…involves more than tracking someone's visual connection to an object; different visual experiences may represent the same thing in different ways" (Low et al., 2016, p. 186). More specifically, the two-system account predicts that the process of tracking whether an object is or is not perceptible to another person (L1-VPT) is relatively effortless and thus should be impervious to constraints on processing opportunity, whereas the process of representing the *way* in which another person interprets the object's identity (L2-VPT) requires effort and thus should be impeded when processing opportunity is constrained (Low et al., 2016). The one-system account, by contrast, proposes that *all* visual perspective tracking is tempered by the specific processing demands of the mentalizing endeavor—that is, it predicts an inverse relationship between constrained processing opportunity and perspective calculation on both tasks. Given that both theoretical accounts posit that perspective calculation in L2-VPT requires effort, we expected that imposing time pressure would reduce estimates of avatar-perspective calculation (and self-perspective detection) in the L2-VPT task.

5. Overview of experiments

We report four experiments and an internal meta-analysis examining the effects of time pressure on component processes underlying altercentric interference in L1-VPT and L2-VPT. Across experiments, we used a response-deadline manipulation to impose time pressure and thereby constrain processing opportunity, and we used PDP analysis to distinguish avatar-perspective calculation from self-perspective detection. In Experiment 1, participants completed either an L1-VPT task or an L2-VPT task (both adapted from Surtees, Samson, et al., 2016, Experiment 1). In the L1-VPT task, participants indicated whether a numerical cue matched the number of objects (i.e., balloons) in a room that were visible either from their own perspective or from a human avatar's perspective. In the L2-VPT task, by contrast, participants indicated whether a numerical cue matched the identity of numerals (6, 9) on a table either from their own perspective or from an avatar's perspective. Both tasks included trials in which self and avatar perspectives were aligned and trials in which self and avatar perspectives were in conflict. Additionally, some blocks of trials in each task had a longer response deadline (1200 ms), whereas other blocks of trials in each task had a shorter response deadline (600 ms)—that is, response deadline was manipulated within subjects. Experiment 2 replicated the procedure of Experiment 1 with a between-subjects manipulation of response deadline (as in Todd et al., 2017, Experiment 1). Finally, in Experiments 3A and 3B, we used a variant of the L2-VPT task in which the numerals to be identified were either asymmetrical (6, 9) and thus looked different from one's own perspective and the avatar's perspective, as before, or symmetrical (1, 8) and thus looked identical from self and avatar perspectives (cf. Surtees, Samson, et al., 2016, Experiment 2).

For each experiment, we report our sample size rationale, as well as all data exclusions, manipulations, and measures. The data for all experiments can be found at https://osf.io/r5s6j/.

6. Experiment 1

6.1. Method

6.1.1. Power and participants

We based our sample size on prior work investigating the operating conditions of altercentric interference in L1-VPT versus L2-VPT (Surtees, Samson, et al., 2016, Experiment 1), settling on a target sample of at least 160 participants (i.e., 2.5 times the size of Surtees et al.'s sample of 64; for elaboration on this rationale, see Simonsohn, 2015). In this and all subsequent experiments, data were collected until we reached or exceeded (in cases of overscheduling) our target sample size. Undergraduates at the University of California, Davis (n = 202) participated for partial course credit. Data from 1 participant were lost to a computer malfunction. We also excluded data from 2 participants who had no valid responses for some trial types, leaving a final sample of 199 participants (159 women, 37 men, 3 unreported).

6.1.2. Procedure and materials

The general procedure and all task materials were identical to those used by Surtees, Samson, et al. (2016, Experiment 1). In all experimental conditions, the critical stimulus was a picture of a cartoon avatar standing in a room next to a table. Participants were randomly assigned to complete either the L1-VPT task or the L2-VPT task. In the L1-VPT task, a varying number of balloons (0, 1, 2, or 3) appeared in the room. On *consistent* trials in this task, all balloons appeared in front of the avatar and thus were clearly visible both to the avatar and to participants; on *inconsistent* trials, some balloons appeared behind the avatar and thus were visible only to participants (see Fig. 2, top panels). In the L2-VPT task, a numeral (6 or 9) appeared on the table. On *consistent* trials in this task, the numeral stood upright and thus looked identical to the avatar and to participants; on *inconsistent* trials, the numeral lay flat and thus appeared as a 6 (9) to the avatar but as a 9 (6) to participants (see Fig. 2, bottom panels). Both tasks included trials in which participants responded from the avatar's perspective (*avatar* trials) and trials in which participants responded from their own perspective (*self* trials). Thus, the L1-VPT task entailed reporting the number of balloons that were visible to the avatar or to oneself, whereas the L2-VPT task entailed reporting the identity of numerals based on how they looked to the avatar or to oneself.

Each trial sequence was as follows: (*i*) a fixation cross signaled the start of the trial (750 ms), (*ii*) a perspective cue (He or You) indicated whose perspective (avatar or self) to verify (750 ms), (*iii*) a numerical content cue indicated the number of balloons in the room to verify (Zero, One, Two, or Three) in the L1-VPT task or the numeral on the table to verify (Six or Nine) in the L2-VPT task (750 ms), and (*iv*) finally the image of the avatar in the room appeared (on screen until participants responded). There was an inter-stimulus interval (500 ms) after (*ii*) and (*iii*). Participants indicated by key press whether the numerical content cue "matches" or "does NOT match" how things look from the cued perspective. Fig. 2 displays the different types of "match" trials in the L1-VPT task (top panels) and the L2-VPT task (bottom panels).

Both tasks comprised 4 blocks of experimental trials; the order of trials within each block was pseudo-randomized according to parameters set by Samson et al. (2010). The L1-VPT task had 208 experimental trials (4 blocks of 52 trials each), and the L2-VPT task had 192 experimental trials (4 blocks of 48 trials each). The higher number of trials on the L1-VPT

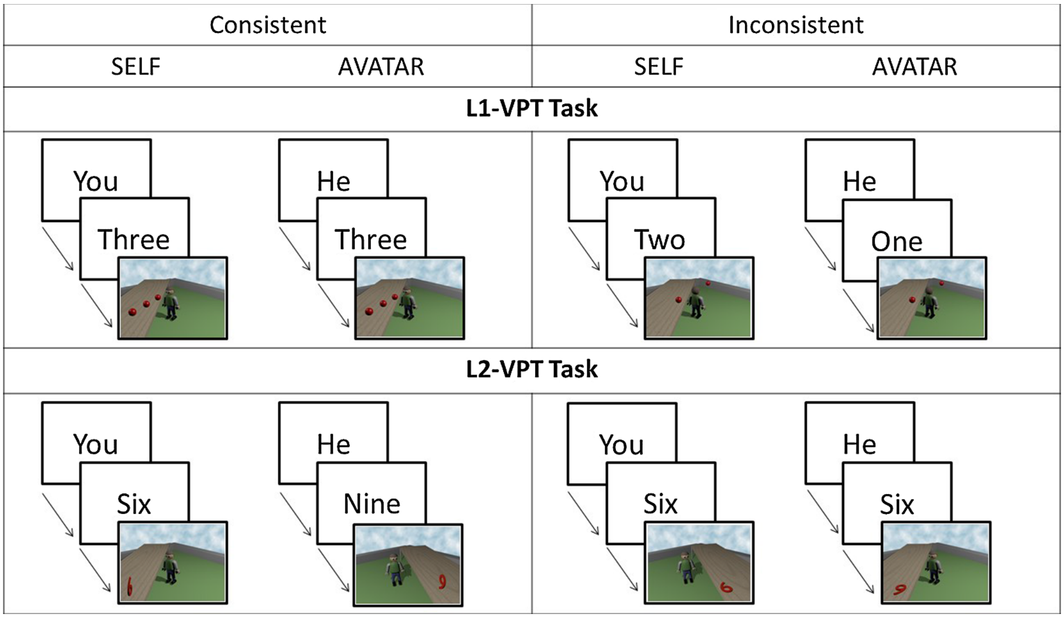

Fig. 2. Examples of "match" trials on the L1-VPT task (top panel) and L2-VPT task (bottom panel). Participants verified if a numerical cue matched the number of balloons visible or the identity of the numeral either from their own perspective (You) or from the avatar's perspective (He). The number of balloons visible and the identity of the numeral from each perspective was either the same (Consistent) or different (Inconsistent).

task reflects the inclusion of "filler" trials to ensure an equal number of "match" responses for each perspective and numerical cue (see Samson et al., 2010; Surtees, Samson, et al., 2016). Additionally, both tasks included 2 blocks of *long-deadline* trials followed by 2 blocks of *short-deadline* trials. Following Todd et al. (2017), the long deadline was set to 1200 ms, and the short deadline was set to 600 ms. If participants responded after the deadline, a message (Please try to respond faster!) appeared for 1 s. If participants responded incorrectly, a red X appeared for 1 s. Practice trials (26 in the L1-VPT task, 24 in the L2-VPT task) preceded the first experimental block of long-deadline trials and the first experimental block of short-deadline trials in both tasks.

6.2. Results and discussion

6.2.1. Analysis plan

Before analysis, we excluded "mismatch" trials because specific constraints of the tasks lead to systematic differences across trial types and can inflate consistency effects (see Samson et al., 2010). Because our focus was on testing the efficiency of processes underlying *altercentric*-interference effects, we only report analyses on the self trials in the main text (analyses on the avatar trials appear in the Supplementary Material). Although our primary interest was in the effects of time pressure on the parameter estimates in PDP analyses, following prior applications of the PDP framework to visual perspective taking (Qureshi & Monk, 2018; Simpson & Todd, 2017; Todd et al., 2017), we also report analyses on the error rates from which the PDP estimates are derived.[3] Whereas some prior work has treated both incorrect responses (i.e., pressing the wrong response key) and responses exceeding the response deadline as errors (e.g., Surtees, Apperly, et al., 2016), in this and all subsequent experiments, we treated only incorrect responses as errors, regardless of whether they fell below or exceeded the response deadline. Given theoretical claims by the two-system account that perspective calculation should operate efficiently in L1-VPT, but not in L2-VPT (Apperly & Butterfill, 2009; Butterfill & Apperly, 2013; Low et al., 2016), we report results separately for the two tasks, even in cases in which the highest-order interaction was not significant in the omnibus analysis. Finally, because our data were not normally distributed, we repeated the analyses reported below using the aligned rank transform (ART) tool, a robust non-parametric method for testing both main and interaction effects in factorial designs (Wobbrock, Findlater, Gergle, & Higgins, 2011).[4] Conclusions based on these non-parametric analyses were nearly identical to those based on the traditional parametric analyses.

6.2.2. Error rates

Table 1 displays inferential statistics on the error rates by condition in Experiment 2. A 2 (Level) × 2 (Deadline) × 2 (Consistency) mixed ANOVA, with repeated measures on the last two factors, yielded main effects of Level (L1-VPT < L2-VPT) and Deadline (long < short). There was also a Consistency main effect (consistent < inconsistent) indicative of altercentric interference. A Level × Consistency interaction further indicated that altercentric interference was weaker on the L1-VPT task than on the L2-VPT task (Surtees, Samson, et al., 2016, Experiment 1). Neither the Level × Deadline interaction nor the Deadline × Consistency interaction approached significance; however, the 3-way interaction was significant.

To further unpack these effects, we conducted separate 2 (Deadline) × 2 (Consistency) ANOVAs on the L1-VPT and L2-VPT tasks. Table 2 displays descriptive statistics on the error rates by condition in Experiment 1. Significant main effects of Deadline and Consistency emerged on both tasks. Although the Deadline × Consistency interaction was not significant on either task, follow-up analyses on the L1-VPT task indicated that, if anything, altercentric interference was directionally *stronger* in the short-deadline condition, $t(97) = 4.58$, $p < .001$, $d_z = 0.46$, than in the long-deadline condition, $t(97) = 4.08$, $p < .001$, $d_z = 0.41$. The pattern of means on the L2-VPT task was

[3] The combination of a response deadline and an added time-pressure manipulation used here necessarily restricts the variance of response times (RTs), which limits their validity as an outcome (Amodio & Swencionis, 2018). Thus, we decided a priori to restrict our behavior-level analyses to the error rates (see Cameron, Payne, et al., 2017; Cameron, Spring, et al., 2017; Payne et al., 2002, for a similar strategy). For the sake of completeness, however, we also report exploratory analyses on the RTs for all experiments in the Supplementary Material.

[4] http://depts.washington.edu/madlab/proj/art/.

Table 1
Analyses of error rates on self trials by condition (Experiment 1).

Effect	$F(df_1, df_2)$	p	η_p^2
Omnibus analysis			
Level	27.95	< .001	0.12
Deadline	66.40	< .001	0.25
Consistency	144.93	< .001	0.42
Level × Deadline	< 1	.643	< 0.01
Level × Consistency	25.40	< .001	0.11
Deadline × Consistency	< 1	.779	< 0.01
Level × Deadline × Consistency	4.01	.047	0.02
L1-VPT task analysis			
Deadline	43.37	< .001	0.31
Consistency	30.28	< .001	0.24
Deadline × Consistency	2.02	.159	0.02
L2-VPT task analysis			
Deadline	26.01	< .001	0.21
Consistency	120.26	< .001	0.55
Deadline × Consistency	2.09	.151	0.02

Notes. All analyses: $df_1 = 1$. Omnibus: $df_2 = 197$. L1-VPT: $df_2 = 97$. L2-VPT: $df_2 = 100$.

Table 2
Mean error rates (in %) on self trials by condition (Experiment 1).

Deadline	Consistent trials	Inconsistent trials	Altercentric interference
L1-VPT task			
Long	2.72 (5.83)	6.89 (9.27)	4.17 (10.10)
Short	8.08 (11.69)	14.37 (13.10)	6.29 (13.59)
L2-VPT task			
Long	4.37 (9.97)	18.65 (13.75)	14.27 (14.69)
Short	11.51 (14.90)	22.97 (15.27)	11.45 (15.95)

Notes. Standard deviations are in parentheses. Altercentric interference = errors on inconsistent trials – errors on consistent trials.

opposite that displayed on the L1-VPT task: Altercentric interference was directionally *weaker* in the short-deadline condition, $t(100) = 7.22$, $p < .001$, $d_z = 0.72$, than in the long-deadline condition, $t(100) = 9.77$, $p < .001$, $d_z = 0.97$.

These results provide suggestive evidence that time pressure may have opposing effects on altercentric interference in L1-VPT versus L2-VPT. Whereas constraining processing opportunity tended to increase altercentric interference on the L1-VPT task, as has been observed in prior work (Qureshi et al., 2010; Todd et al., 2017), it tended to decrease altercentric interference on the L2-VPT task.[5] Because neither lower-order effect was significant, however, these results are inconclusive on the effects of time pressure in the two tasks. We next turned to PDP analyses to estimate two component processes that contribute to this behavioral effect and to examine how time pressure affects these processes.

6.2.3. PDP estimates

Using Eqs. (3) and (4) described earlier, for each participant we computed estimates of self-perspective detection and avatar-perspective calculation separately for the long-deadline and short-deadline conditions. In cases of perfect task performance (self-perspective detection = 1), avatar-perspective calculation is undefined, so we applied an adjustment commonly used in PDP analysis (Payne et al., 2002; Todd, Thiem, & Neel, 2016; see also Snodgrass & Corwin, 1988, for an earlier application to signal-detection analysis). Because negative self-perspective detection estimates violate assumptions of the PDP that parameter estimates range from 0 to 1 (Jacoby, 1991), we replaced such instances with 0 (Lundberg, Neel, Lassetter, & Todd, 2018); however, retaining the original (negative) self-perspective detection estimates produced nearly identical results. We followed this same procedure for computing parameter estimates in all subsequent experiments.

Table 3 displays inferential statistics on the PDP estimates by condition in Experiment 1. Given prior work suggesting that time pressure dampens self-perspective detection in L1-VPT (Todd et al., 2017), and findings from multiple studies suggesting that time pressure reduces conceptual analogues of this parameter in other paradigms (e.g., Cameron, Payne, et al., 2017; Cameron, Spring, et al., 2017; Payne, 2001; Payne et al., 2002), we anticipated that time pressure would reduce self-perspective detection on both tasks. A 2 (Level) × 2 (Deadline) mixed ANOVA on the self-perspective detection estimates (see Fig. 3, left side) revealed a main effect of Level indicating that, overall, detection of one's own perspective was weaker on the L2-VPT task than on the L1-VPT task. There was also a significant Deadline main effect that was not moderated by Level. Follow-up analyses indicated that self-perspective detection was weaker in the short-deadline condition than in the long-deadline condition—an effect that emerged on both the L1-VPT task, $t(97) = 6.93$, $p < .001$, $d_z = 0.70$, and the L2-VPT task, $t(100) = 5.22$, $p < .001$, $d_z = 0.52$.

The two-system account of mentalizing predicts that constraining processing opportunity should weaken avatar-perspective calculation in the L2-VPT task but not in the L1-VPT task, whereas the one-system account predicts that constraining processing opportunity should weaken avatar-perspective calculation in both tasks. In an identical ANOVA on the avatar-perspective calculation estimates (see Fig. 3, right side), the Level × Deadline interaction was significant. Decomposing this interaction revealed that calculation of the avatar's perspective was weaker in the short-deadline condition than in the long-deadline condition on the L2-VPT task, $t(100) = 2.39$, $p = .019$, $d_z = 0.24$; however, replicating Todd et al. (2017), the effect of deadline on avatar-perspective calculation was not significant on the L1-VPT task ($t < 1$, $p = .362$, $d_z = -0.09$). There was also a significant main effect of Level indicating that, overall, avatar-perspective calculation was weaker on the L1-VPT task than on the L2-VPT task. The Deadline main effect was not significant.

Several noteworthy findings emerged in Experiment 1: The error-rate analyses provided unambiguous evidence for the presence of altercentric interference in both the L1-VPT task, replicating many previous studies, and the L2-VPT task, replicating several prior studies (Elekes et al., 2016, 2017; Surtees, Apperly, et al., 2016; Surtees, Samson, et al., 2016). The error-rate analyses also provided suggestive, though ultimately inconclusive, evidence that time pressure had opposing effects on altercentric interference in the two tasks. The ambiguity of these results points to a key strength of the process-dissociation approach: the ability to disentangle component processes underlying altercentric-interference effects. As expected based on prior work, time pressure reduced self-perspective detection in both the L1-VPT task (Todd et al., 2017) and the L2-VPT task. Finally, and arguably most important for the current research, time pressure also reduced avatar-perspective calculation, but only on the L2-VPT task. The effect of time pressure on avatar-perspective calculation was negligible on the L1-VPT task (Todd et al., 2017). Together, these findings provide the first empirical support for the theoretical claim of the two-system account of mentalizing that the incidental calculation of other agents' perspectives operates independent of processing opportunity in L1-VPT, but not in L2-VPT (Apperly & Butterfill, 2009; Butterfill & Apperly, 2013; Low et al., 2016).

7. Experiment 2

A potential limitation of Experiment 1 was that the long-deadline trials and short-deadline trials appeared in a fixed order, with the

[5] Though not the focus of the current work, across experiments, we observed evidence that time pressure increased egocentric interference in L2-VPT. These results, which are detailed in the Supplementary Material, suggest that the current findings cannot be explained as time pressure reducing interference from any irrelevant perspective.

Table 3
Analyses of PDP estimates of self-perspective detection and avatar-perspective calculation by condition (Experiment 1).

Effect	$F(df_1, df_2)$	p	η_p^2
Self-perspective detection			
Level	30.42	< .001	0.13
Deadline	70.31	< .001	0.26
Level × Deadline	< 1	.776	< 0.01
Avatar-perspective calculation			
Level	22.66	< .001	0.10
Deadline	1.11	.293	< 0.01
Level × Deadline	5.49	.020	0.03

Notes. Both analyses: $df_1 = 1$, $df_2 = 197$.

former trials preceding the latter trials for all participants. We reasoned that presenting the trials in the reversed order or counterbalancing block order would introduce the potential for carry-over effects (i.e., participants who are forced to respond quickly early in the task may continue doing so later in the task; see Payne et al., 2002, for similar logic). Because using a fixed block order necessarily confounds deadline with time spent working on the task, however, it is uncertain whether the observed effects are attributable to increased time pressure in the short-deadline trials or to increased fatigue in the later blocks of trials. Although we considered fatigue an unlikely explanation for the results observed in Experiment 1, we nevertheless address this issue in Experiment 2 by using a between-subjects manipulation of response deadline.

7.1. Method

7.1.1. Power and participants

We based our sample size on the Level × Deadline interaction on avatar-perspective calculation in Experiment 1 ($\eta_p^2 = 0.03$), settling on a target sample of at least 256 participants for 80% a priori power (Faul, Erdfelder, Lang, & Buchner, 2007). Undergraduates at the University of California, Davis ($n = 287$) participated for partial course credit. Following prior work (Surtees, Samson, et al., 2016; Todd et al., 2017), we excluded data from participants ($n = 6$) whose task performance was at or below chance (≤50% accuracy), which could indicate confusion about response-key mappings or task instructions. We also excluded data from 1 participant who had no valid responses for some trial types. Data from 3 additional participants were lost to computer malfunctions, leaving a final sample of 277 participants (227 women, 47 men, 3 unreported).

7.1.2. Procedure and materials

The general procedure and all task materials were identical to those from Experiment 1, except we manipulated both Level and Deadline on a between-subjects basis. Participants were randomly assigned to complete either the L1-VPT task or the L2-VPT task, and the response deadline for all trials within each task was either 1200 ms in the long-deadline condition or 600 ms in the short-deadline condition.

7.2. Results and discussion

7.2.1. Error rates

Table 4 displays inferential statistics on the error rates by condition in Experiment 2. A 2 (Level) × 2 (Deadline) × 2 (Consistency) mixed ANOVA, with repeated measures on the last factor, yielded main effects of Level (L1-VPT < L2-VPT), Deadline (long < short), and Consistency (consistent < inconsistent). A Level × Consistency interaction further indicated that, as in Experiment 1 (cf. Surtees, Samson, et al., 2016, Experiment 1), altercentric interference was weaker on the L1-VPT task than on the L2-VPT task. Neither the Deadline × Consistency interaction nor the 3-way interaction was significant.

To further unpack these effects, we again conducted separate 2 (Deadline) × 2 (Consistency) ANOVAs on the L1-VPT and L2-VPT tasks.

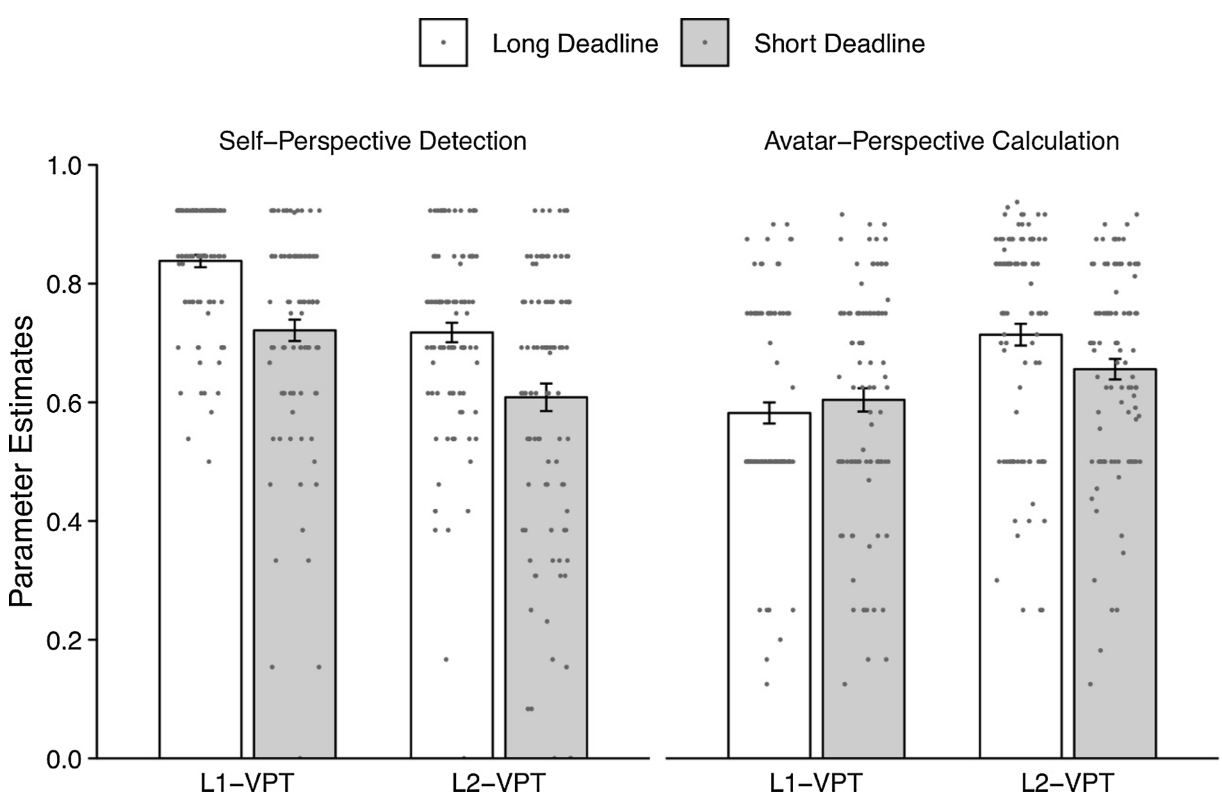

Fig. 3. PDP estimates of self-perspective detection and avatar-perspective calculation by level (L1-VPT vs. L2-VPT) and deadline (long vs. short) in Experiment 1. Error bars depict standard errors; dots depict individual data points.

Table 4
Analyses of error rates on self trials by condition (Experiment 2).

Effect	$F(df_1, df_2)$	p	η_p^2
Omnibus analysis			
Level	10.72	.001	0.04
Deadline	28.86	< .001	0.10
Consistency	237.12	< .001	0.47
Level × Deadline	1.67	.197	< 0.01
Level × Consistency	32.92	< .001	0.11
Deadline × Consistency	< 1	.603	< 0.01
Level × Deadline × Consistency	< 1	.662	< 0.01
L1-VPT task analysis			
Deadline	8.38	.004	0.06
Consistency	74.81	< .001	0.36
Deadline × Consistency	< 1	.941	< 0.01
L2-VPT task analysis			
Deadline	22.09	< .001	0.14
Consistency	165.68	< .001	0.54
Deadline × Consistency	< 1	.561	< 0.01

Notes. All analyses: $df_1 = 1$. Omnibus: $df_2 = 273$. L1-VPT: $df_2 = 134$. L2-VPT: $df_2 = 139$.

Table 5 displays descriptive statistics by condition in Experiment 2. Significant main effects of Deadline and Consistency emerged on both tasks, whereas the Deadline × Consistency interaction was not significant on either task. Follow-up analyses revealed significant altercentric interference in both the long-deadline condition, $t(69) = 6.87$, $p < .001$, $d_z = 0.82$, and the short-deadline condition, $t(65) = 5.53$, $p < .001$, $d_z = 0.68$, on the L1-VPT task. There was also significant altercentric interference in both the long-deadline condition, $t(69) = 10.80$, $p < .001$, $d_z = 1.29$, and the short-deadline condition, $t(70) = 8.21$, $p < .001$, $d_z = 0.97$, on the L2-VPT task.

The error-rate results were less ambiguous in Experiment 2 than in Experiment 1. Despite increasing error rates overall, time pressure failed to produce detectable changes in altercentric interference on either task. Indeed, significant altercentric interference emerged in all experimental conditions. As before, we next turned to PDP analyses to determine whether and how time pressure affected component processes underlying these behavioral effects.

7.2.2. PDP estimates

Table 6 displays inferential statistics on the PDP estimates by condition in Experiment 2. A 2 (Level) × 2 (Deadline) ANOVA on the self-perspective detection estimates (see Fig. 4, left side) revealed a main effect of Level indicating that, overall, self-perspective detection was weaker on the L2-VPT task than on the L1-VPT task. There was also a significant Deadline main effect that was not moderated by Level. As in Experiment 1, detection of one's own perspective was weaker in the short-deadline condition than in the long deadline-condition on the L1-VPT task, $t(134) = 2.69$, $p = .008$, $d_s = 0.46$, replicating Todd et al. (2017), and on the L2-VPT task, $t(139) = 4.57$, $p < .001$, $d_s = 0.77$.

An identical ANOVA on the avatar-perspective calculation estimates (see Fig. 4, right side) yielded main effects of Level (L1-VPT < L2-VPT)

Table 5
Mean error rates on self trials by condition (Experiment 2).

Deadline	Consistent trials	Inconsistent trials	Altercentric interference
L1-VPT task			
Long	5.54 (8.59)	11.67 (11.52)	6.13 (7.46)
Short	10.38 (10.78)	16.62 (11.72)	6.24 (9.17)
L2-VPT task			
Long	4.52 (8.39)	17.44 (12.11)	12.92 (10.01)
Short	11.91 (12.02)	26.06 (14.22)	14.14 (14.51)

Notes. Standard deviations are in parentheses. Altercentric interference = errors on inconsistent trials – errors on consistent trials.

Table 6
Analyses of PDP estimates of self-perspective detection and avatar-perspective calculation by condition (Experiment 2).

Effect	$F(df_1, df_2)$	p	η_p^2
Self-perspective detection			
Level	10.66	.001	0.04
Deadline	26.40	< .001	0.09
Level × Deadline	1.88	.172	< 0.01
Avatar-perspective calculation			
Level	21.85	< .001	0.07
Deadline	4.19	.043	0.02
Level × Deadline	1.63	.203	< 0.01

Notes. Both analyses: $df_1 = 1$, $df_2 = 277$.

and Deadline (short < long). Unlike Experiment 1, the Level × Deadline interaction was not significant, suggesting that deadline did not have differential effects on avatar-perspective calculation in the L1-VPT and L2-VPT tasks. As in Experiment, 1, however, follow-up analyses indicated that calculation of the avatar's perspective was weaker in the short-deadline condition than in the long-deadline condition, but only on the L2-VPT task, $t(139) = 2.44$, $p = .016$, $d_s = 0.41$. Avatar-perspective calculation did not significantly differ across the deadline conditions on the L1-VPT task ($t < 1$, $p = .601$, $d_s = 0.09$), again replicating Todd et al. (2017).

The results of the PDP analyses in Experiment 2 generally replicated those obtained in Experiment 1: Whereas time pressure reduced self-perspective detection on both tasks, it only reduced avatar-perspective calculation on the L2-VPT task. Unlike Experiment 1, however, the Level × Deadline interaction on avatar-perspective calculation was not significant in Experiment 2. Together, the results of Experiments 1 and 2, in conjunction with the negligible effect of time pressure on avatar-perspective calculation in L1-VPT reported by Todd et al. (2017), suggest that calculating other agents' visual perspectives appears to be an efficient process in L1-VPT (contra Qureshi & Monk, 2018), but not in L2-VPT (Apperly & Butterfill, 2009; Butterfill & Apperly, 2013; Low et al., 2016).

8. Experiments 3A and 3B

Although efforts were made in Experiments 1 and 2 (and by Surtees, Samson, et al., 2016) to equate the L1-VPT and L2-VPT tasks structurally, the set of relevant numerical stimuli was smaller in the L2-VPT task (6, 9) than in the L1-VPT task (0, 1, 2, and 3), which may have resulted in lower task demands in the former task than in the latter task. Several findings from Experiments 1 and 2 (e.g., stronger altercentric interference and more errors overall in the L2-VPT task than in the L1-VPT task) challenge this possibility, however. Nevertheless, in Experiments 3A and 3B, we modified the L2-VPT task so that the stimulus set comprised four numerals instead of two. Specifically, along with asymmetrical numerals (6, 9) that have different identities when viewed from one's own versus the avatar's physical vantage point, we also included symmetrical numerals (1, 8) that have the same identity when viewed from either perspective (Elekes et al., 2016, 2017; Surtees et al., 2012; Surtees, Samson, et al., 2016, Experiment 2). Experiment 3A, like Experiment 1, used a within-subjects manipulation of response deadline, whereas Experiment 3B, like Experiment 2, used a between-subjects manipulation of response deadline. Having repeatedly found null effects of time pressure on avatar-perspective calculation in L1-VPT in Experiments 1 and 2 and elsewhere (Todd et al., 2017), we had all participants complete only the L2-VPT task in Experiments 3A and 3B.

8.1. Method

8.1.1. Power and participants

We based our sample sizes on the simple effect of Deadline on

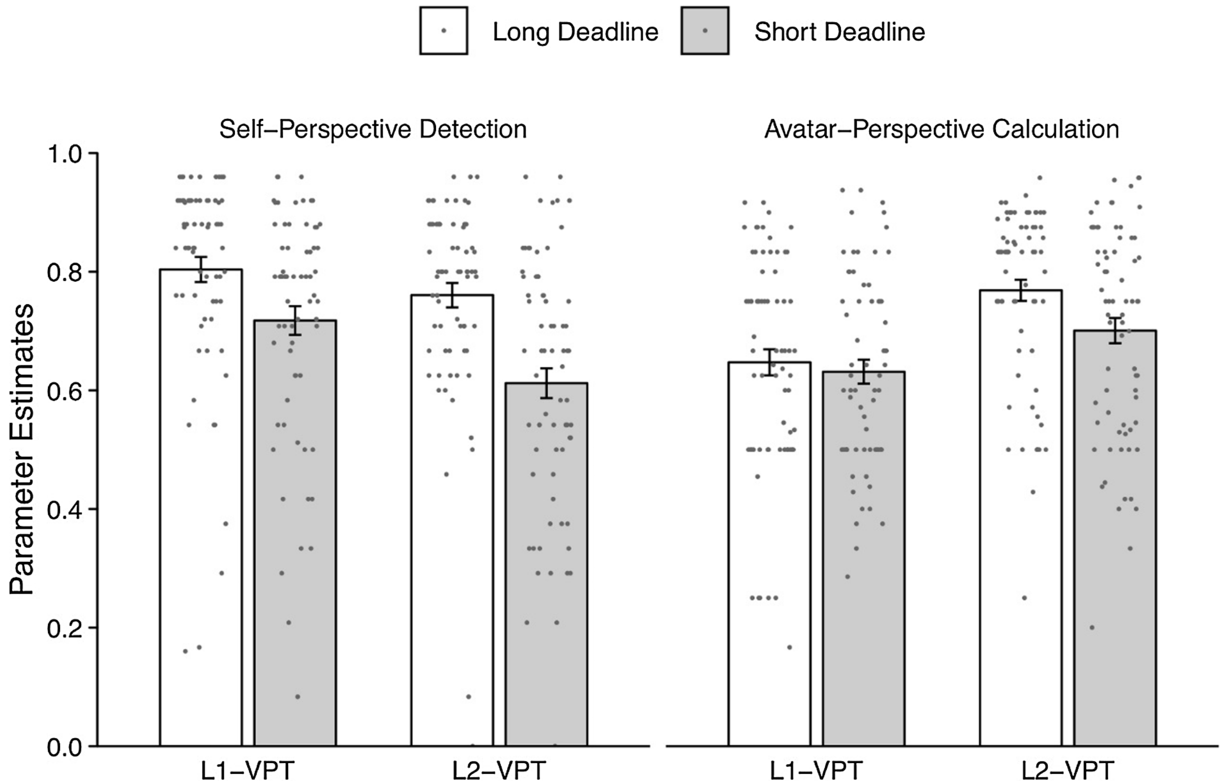

Fig. 4. PDP estimates of self-perspective detection and avatar-perspective calculation by level (L1-VPT vs. L2-VPT) and deadline (long vs. short) in Experiment 2. Error bars depict standard errors; dots depict individual data points.

avatar-perspective calculation on the L2-VPT task in Experiment 1 ($d_z = 0.24$) and Experiment 2 ($d_s = 0.41$), respectively, settling on target samples of at least 139 participants in Experiment 3A and at least 190 participants in Experiment 3B for 80% a priori power (Faul et al., 2007). Because data collection for Experiment 3B began near the end of an academic term, we planned a sequential analysis (Lakens, 2014) that would allow us to analyze our data at two time intervals (an interim analysis at the end of the academic term and a final analysis after reaching the target sample size) while maintaining an overall Type I error rate of 5%. The pre-registered analysis plan can be found at https://aspredicted.org/blind.php?x=as62v6. At the end of the academic term, our sample size was 124 (~65% of our target sample). Using a linear spending function, we calculated alpha boundaries of .033 and .031 for the two analyses based on Lakens' (2014) instructions for the WinDL freeware program (Reboussin, DeMets, Kim, & Lan, 2000). Because the observed *p*-value of .041 in the interim analysis exceeded the alpha boundary of .033, we continued data collection until reaching our target sample size in Experiment 3B.

Undergraduates at the University of California, Davis (Experiment 3A: $n = 151$; Experiment 3B: $n = 190$) participated either for partial course credit or for a $10 Amazon gift card. As before, we excluded data from participants (Experiment 3A: $n = 1$; Experiment 3B: $n = 3$) who performed at or below chance. Data from several additional participants (Experiment 3B: $n = 3$) were lost to computer malfunctions. Together, these exclusions left final samples of 150 participants in Experiment 3A (92 women, 53 men, 4 reporting a non-binary gender identity, 1 unreported) and 184 participants in Experiment 3B (130 women, 51 men, 3 reporting a non-binary gender identity).

8.1.2. Procedure and materials

The general procedure and task materials in Experiments 3A and 3B were identical to those from Experiments 1 and 2, respectively, except here all participants only completed the L2-VPT task. Both experiments also included a larger set of numerical stimuli, and all numerals lay flat on the table (as in Surtees, Samson, et al., 2016, Experiment 2). On *consistent* trials, the numeral (1 or 8) was symmetrical and thus looked identical from the avatar's perspective and participants' own perspective; on *inconsistent* trials, the numeral (6 or 9) was asymmetrical and thus looked different from the two perspectives. The numerical cues were uniquely paired with the specific trial types; that is, consistent trials were cued with One or Eight, and inconsistent trials were cued with Six or Nine. In Experiment 3A, like Experiment 1, all participants completed 2 blocks of long-deadline trials (1200 ms) followed by 2 blocks of short-deadline trials (600 ms). In Experiment 3B, like Experiment 2, participants were randomly assigned to either a long-deadline condition or a short-deadline condition, and the response deadline (1200 ms or 600 ms) remained constant throughout the task.

8.2. Results and discussion

8.2.1. Error rates

Tables 7 and 8 display inferential statistics and descriptive statistics, respectively, on the error rates by condition in Experiments 3A and 3B. A 2 (Deadline) × 2 (Consistency) repeated-measures ANOVA in Experiment 3A and mixed ANOVA in Experiment 3B yielded main effects of Deadline (short < long) and Consistency (consistent < inconsistent) in both experiments. The Deadline × Consistency interaction was marginally significant in Experiment 3A and non-significant in Experiment 3B.

Follow-up analyses in Experiment 3A revealed significant altercentric interference in both the short-deadline condition, $t(149) = 4.55$, $p < .001$, $d_z = 0.37$, and the long-deadline condition, $t(149) = 7.68$, $p < .001$, $d_z = 0.63$. These results replicated in Experiment 3B: Significant altercentric interference emerged in both the short-deadline condition, $t(91) = 4.79$, $p < .001$, $d_z = 0.50$, and the long-deadline condition, $t(91) = 6.22$, $p < .001$, $d_z = 0.68$.

Table 7
Analyses of error rates on self trials by condition (Experiments 3A and 3B).

Effect	$F(df_1, df_2)$	p	η_p^2
Experiment 3A			
Deadline	16.71	< .001	0.10
Consistency	63.54	< .001	0.30
Deadline × Consistency	3.42	.066	0.02
Experiment 3B			
Deadline	13.77	< .001	0.07
Consistency	60.07	< .001	0.25
Deadline × Consistency	< 1	.441	< 0.01

Notes. Both experiments: $df_1 = 1$. Experiment 3A: $df_2 = 149$. Experiment 3B: $df_2 = 182$.

Table 8
Mean error rates on self trials by condition (Experiments 3A and 3B).

Deadline	Consistent trials	Inconsistent trials	Altercentric interference
Experiment 3A			
Long	3.33 (5.95)	10.78 (11.96)	7.44 (11.87)
Short	7.50 (9.45)	12.44 (13.78)	4.94 (13.31)
Experiment 3B			
Long	3.90 (6.96)	10.42 (10.58)	6.53 (10.06)
Short	6.32 (8.20)	12.25 (10.78)	5.94 (10.38)

Notes. Standard deviations are in parentheses. Altercentric interference = errors on inconsistent trials – errors on consistent trials.

8.2.2. PDP estimates

Self-perspective detection (see Fig. 5, left side) was weaker in the short-deadline condition than in the long-deadline condition—an effect that emerged in Experiment 3A, $t(149) = 4.09$, $p < .001$, $d_z = 0.33$, and in Experiment 3B, $t(182) = 3.42$, $p = .001$, $d_s = 0.50$. More important, avatar-perspective calculation (see Fig. 5, right side) was also weaker in the short-deadline condition than in the long-deadline condition in both Experiment 3A, $t(149) = 2.59$, $p = .011$, $d_z = 0.21$, and Experiment 3B, $t(182) = 2.21$, $p = .029$, $d_s = 0.33$.

The results of Experiments 3A and 3B conceptually replicate those from Experiments 1 and 2 using both within-subjects and between-subjects manipulations of response deadline and a larger numerical stimulus set in the L2-VPT task. Whereas time pressure had weak and inconclusive effects on altercentric interference in the error-rate analyses, it consistently reduced estimates of avatar-perspective calculation (and self-perspective detection) in the PDP analyses.

9. General discussion

In four experiments, we investigated the effects of time pressure on the incidental calculation of *what* other agents see—level-1 visual perspective taking (L1-VPT)—and *how* they see it—level-2 visual perspective taking (L2-VPT). Departing from prior research that has typically treated altercentric-interference effects in indirect measures of visual perspective taking as providing a “process-pure” index of perspective calculation, or “implicit mentalizing,” we used the process-dissociation procedure (PDP) to estimate two component processes underlying altercentric-interference effects: the direct reporting of one’s own visual perspective (self-perspective detection) and the incidental encoding of the avatar’s visual perspective (avatar-perspective calculation). Critically, rather than assuming (based on the indirectness of the measurement procedure) that this latter process parameter operates automatically, we used a response-deadline manipulation to directly examine whether this process displays a specific feature of automaticity: resource efficiency (Bargh, 1994).

Several key results consistently emerged across our experiments: First, imposing time pressure reduced self-perspective detection in both L1-VPT and L2-VPT. Second, and more important, time pressure also reduced avatar-perspective calculation, but only in L2-VPT; calculation of the avatar’s perspective was relatively unaffected by time pressure in L1-VPT. Third, we observed this general pattern using both within-subjects and between-subjects manipulations of time pressure and two different variants of the L2-VPT task. Fourth, we did not observe these same effects of time pressure on altercentric interference in the error-rate analyses, despite consistently seeing evidence for the presence of altercentric interference on both tasks. This divergence in findings between the error-rate analyses and the PDP analyses highlights the utility of the PDP in estimating component processes underlying perspective taking. Together, these findings generally align with the two-system account’s claim that tracking what object(s) another agent sees is not constrained by limited processing resources, whereas encoding how the agent sees the object(s) requires ample processing opportunity (Apperly & Butterfill, 2009; Butterfill & Apperly, 2013; Low et al., 2016).

9.1. Meta-analytic summary

Guided by recent recommendations urging researchers to consider the totality of information that can be ascertained from a program of research rather than from single experiments in isolation (e.g., Braver, Thoemmes, & Rosenthal, 2014; Ledgerwood, in press), we ran a series of meta-analytic tests to quantify the cumulative effect of time pressure on self-perspective detection and avatar-perspective calculation in L1-VPT and L2-VPT.[6] We conducted these analyses with McShane and Böckenholt's (2017) single-paper meta-analysis tool.[7]

In a first set of analyses, we examined contrasts reflecting the simple effect of Deadline on self-perspective detection separately in the L1-VPT task (contrast code: 1 –1 0 0) and in the L2-VPT task (contrast code: 0 0 1 –1). This contrast was significant for both tasks (L1-VPT: Estimate = 0.11, $CI_{95\%}$ [0.08, 0.15], $z = 5.98$, $p < .001$; L2-VPT: Estimate = 0.09, $CI_{95\%}$ [0.06, 0.13], $z = 5.20$, $p < .001$). Furthermore, a contrast reflecting the Level × Deadline interaction (contrast code: 1 – 1 –1 1) was not significant (Estimate = 0.02, $CI_{95\%}$ [−0.03, 0.07], $z < 1$, $p = .446$), These results, which suggest that constraining processing opportunity via time pressure led to comparable reductions in self-perspective detection on the two tasks, replicate prior findings indicating that time pressure reduces self-perspective detection on the L1-VPT task (Todd et al., 2017). More generally, these findings comport with those from multiple other studies reporting similar effects of time pressure on conceptual analogues of this process parameter in other paradigms (e.g., Cameron, Payne, et al., 2017; Cameron, Spring, et al., 2017; Payne, 2001; Payne et al., 2002).

In a second set of analyses, we examined these same contrasts on avatar-perspective calculation, the construct of focal interest in the current work. Here, the simple effect of Deadline was significant on the L2-VPT task (Estimate = 0.06, $CI_{95\%}$ [0.04, 0.09], $z = 4.78$, $p < .001$), but not on the L1-VPT task (Estimate = −0.26, $CI_{95\%}$ [−0.04, 0.03], $z < 1$, $p = .792$). This pattern of differential effects of time pressure on the two tasks produced a significant Level × Deadline interaction (Estimate = −0.07, $CI_{95\%}$ [−0.11, −0.02], $z = 2.85$, $p = .004$). These results suggest that calculating the avatar’s visual perspective appears to be a relatively efficient process in L1-VPT, replicating Todd et al. (2017). In L2-VPT, however, avatar-perspective calculation appears to be relatively inefficient, in that it was reduced under conditions of limited processing opportunity. These latter results align conceptually with results reported by Schneider, Lam, Bayliss, and Dux (2012), who found that constraining processing opportunity via a dual-task paradigm undermined the incidental tracking of other agents’ *beliefs*, as assessed with eye-tracking methodology.

Together, these findings lend additional support to the two-system

[6] These are the only experiments we have conducted on the effects of time pressure on L1-VPT and L2-VPT task performance (i.e., there is no file drawer).

[7] http://www.singlepapermetaanalysis.com.

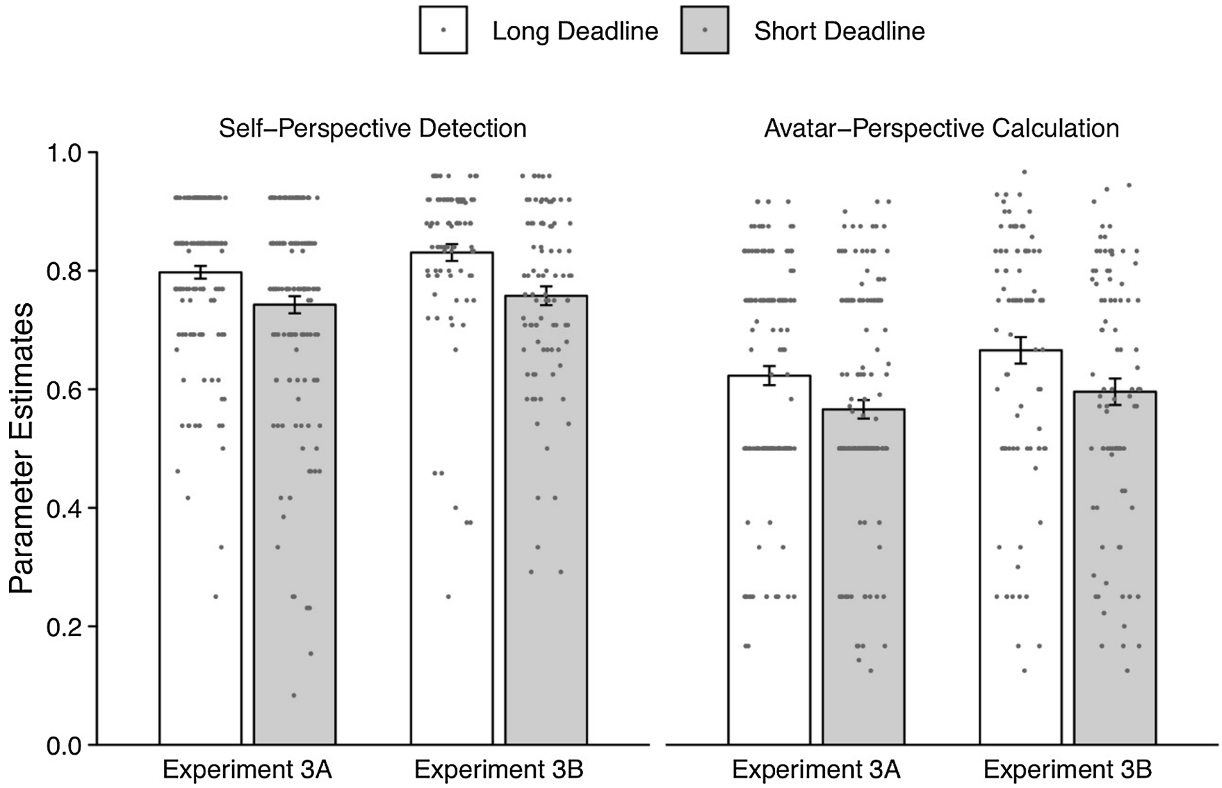

Fig. 5. PDP estimates of self-perspective detection and avatar-perspective calculation in the L2-VPT task by deadline (long vs. short) in Experiments 3A and 3B. Error bars depict standard errors; dots depict individual data points.

account, which maintains that encoding other people's level-1 perspectives is efficient, whereas representing other people's beliefs and level-2 perspectives is not (Apperly & Butterfill, 2009; Butterfill & Apperly, 2013; Low et al., 2016). Notably, had we simply analyzed altercentric interference as a behavioral effect, as is customary in research using indirect measures to make claims about incidental perspective tracking, our conclusions would have been different. Indeed, in an identical set of meta-analytic tests on an index of altercentric interference (errors on inconsistent trials – errors on consistent trials), the Deadline simple effect was not significant on either task (L1-VPT: Estimate = −0.95%, $CI_{95\%}$ [−3.11, 1.21], $z < 1$, $p = .387$; L2-VPT: Estimate = 1.49%, $CI_{95\%}$ [−0.20, 3.18], $z = 1.73$, $p = .084$), nor was the Level × Deadline interaction (Estimate = −2.44%, $CI_{95\%}$ [−5.19, 0.30], $z = 1.75$, $p = .081$).[8] That time pressure did *not* significantly reduce altercentric interference in the error-rate analyses on either task could lead one to conclude that both types of perspective taking operate efficiently. This conclusion, though contrary to the conclusions based on the results of the PDP analyses, would be entirely consistent with the typical interpretation of altercentric interference on indirect measures as reflecting a process-pure index of perspective calculation.

In sum, the current findings illustrate the utility of the PDP framework for unmasking effects of theoretical interest that may otherwise go under-detected in behavioral data when restricting analyses to error rates. By isolating the incidental calculation of other agents' visual perspectives—the core construct of interest in indirect measures of visual perspective taking—from the deliberate detection of one's own perspective, the PDP framework helps clarify how time pressure affects component processes underlying altercentric interference. Using this approach, furthermore, we were able to examine these processes in a way that afforded a test between competing theoretical accounts of mentalizing, thereby illustrating how a methodological tool can be implemented to test and advance theory (Greenwald, 2012).

9.2. Implications, limitations, and future research directions

These experiments provide initial empirical evidence for systematic differences in the efficiency of incidental perspective tracking in L1-VPT versus L2-VPT. Whereas calculating what objects another agent can see seems to operate regardless of whether one has ample processing opportunity, calculating the identity of those objects from that agent's perspective seems to be contingent on having sufficient processing opportunity. Based on the current results and on those reported elsewhere (e.g., Surtees, Apperly, et al., 2016; Surtees, Samson, et al., 2016), we suggest that one is most likely to incidentally encode *how* an object appears to another agent (i.e., to engage in level-2 perspective calculation) when one has ample processing resources and the other agent's perspective is relevant to one's own current (overt or covert) processing goals. Furthermore, it seems that such perspective calculation occurs even though it is costly to one's own task performance.

Granted, because each of our experiments used similar variants of a single L2-VPT task (Surtees et al., 2012; Surtees, Samson, et al., 2016), we acknowledge that the current findings are most informative for understanding the efficiency of level-2 perspective calculation in this specific task. A tacit assumption of this task is that the avatar shares the participant's focal goal of determining the identity of the numeral. Other studies have used L2-VPT tasks in which participants interact with another participant whose perspective and focal task goal differ from those of the participant. For example, Surtees, Apperly, et al. (2016) observed evidence of altercentric interference in an L2-VPT task in which participants had a goal of identifying the magnitude of a

[8] An analogous set of exploratory meta-analytic tests on the RTs in the self trials revealed that time pressure reduced altercentric interference in both L1-VPT and L2-VPT, but this effect was stronger in L2-VPT than in L2-VPT (see the Supplementary Material for details). These results, which suggest that incidental perspective tracking is *relatively less* efficient in L2-VPT than in L1-VPT, can arguably be accommodated by both the two-system and the one-system accounts of mentalizing.

numeral (i.e., whether the numeral is bigger than 7) that had a different identity from their own perspective and their interaction partner's perspective (e.g., 6), even when participants explicitly knew their interaction partner had a different task goal of identifying a superficial surface feature of the same numeral (i.e., whether the numeral is spotted). Their results suggest that, at least in interactive contexts, the incidental tracking of level-2 perspectives may not be contingent on the target person's having the same focal processing goal as participants do (cf. Elekes et al., 2016). Accordingly, we view the current work as a starting point in understanding the efficiency of perspective calculation in L2-VPT. Future research using different, and perhaps more interactive, L2-VPT tasks will be needed for a more complete understanding of the efficiency (or lack thereof) of level-2 perspective calculation.

Here, we acknowledge several other limitations of the current work, each of which suggests additional potential directions for future research. First, across experiments, we examined efficiency by limiting the time participants had to process and respond to the visual information depicted in the tasks. Although imposing time pressure is a common method for investigating how efficiently different cognitive processes operate, it is possible that other means of constraining processing opportunity (e.g., dual-task paradigm) would produce different results. In line with this possibility, Qureshi and Monk (2018) found that concurrently performing a working-memory task reduced both self-perspective detection and avatar-perspective calculation in L1-VPT. As noted earlier, however, a PDP re-analysis of Qureshi et al.'s (2010) data revealed that simultaneously performing a motor-inhibition task reduced self-perspective detection, but it did not affect avatar-perspective calculation (Qureshi & Monk, 2018). A tentative conclusion from these divergent findings is that perspective calculation in L1-VPT is undermined by concurrent tasks that tax working memory but may be largely resistant to time pressure and concurrent tasks that require motor inhibition; however, a more complete understanding of the efficiency of perspective calculation will require additional research that systematically examines different methods for constraining processing opportunity. For example, future experiments could explore whether and how time pressure and working memory load interact to affect processes underlying visual perspective taking (cf. Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007).

Second, each of our experiments retained the same response deadlines used by Todd et al. (2017) for the long-deadline and short-deadline conditions: 1200 ms and 600 ms, respectively. Although 600 ms is considerably shorter than 1200 ms, both are shorter than the 2000 ms response deadline most commonly used in similar visual perspective-taking tasks. By including a range of response deadlines, future research could determine if perspective calculation decreases linearly with increasing time pressure or if there is a curvilinear relationship wherein perspective calculation is most pronounced when processing opportunity is neither too low nor too high.

Third, across experiments, we used task designs in which the self trials and the avatar trials were intermixed within the same blocks of trials. Although such mixed-block designs nicely capture the switching between one's own and another's perspective that is often required in daily life, these designs also introduce the possibility of carry-over effects that can magnify altercentric interference. For example, Surtees, Samson, et al. (2016) found that altercentric interference in L2-VPT, but not in L1-VPT, was weaker when self trials and avatar trials appeared in separate blocks of trials than when they were intermixed in the same blocks of trials. These findings suggest that level-2 perspective tracking may be goal-dependent, in that altercentric interference was stronger when the structure of the task itself elicited a covert goal to consider the avatar's perspective (see Bargh, 1989). Future research should examine the efficiency (or lack thereof) of perspective calculation using task designs that minimize the possibility of carry-over effects from having just considered the avatar's perspective on a preceding trial in the same block.

Finally, there is ongoing debate about whether altercentric-interference effects in L1-VPT capture processes that are specifically social in nature (i.e., the "mentalizing" interpretation) or whether they reflect domain-general processes, such as attentional cueing (i.e., the "sub-mentalizing" interpretation; Heyes, 2014). Experiments designed to test between these accounts have produced mixed results, with some findings supporting the mentalizing interpretation (e.g., Baker, Levin, & Saylor, 2016; Bukowski, Hietanen, & Samson, 2015; Furlanetto, Becchio, Samson, & Apperly, 2016; Gardner, Bileviciute, & Edmonds, 2018; Michael et al., 2018; Nielsen, Slade, Levy, & Holmes, 2015) and other findings supporting the sub-mentalizing interpretation (e.g., Cole, Atkinson, Le, & Smith, 2016; Conway, Lee, Ojaghi, Catmur, & Bird, 2017; Gardner, Hull, Taylor, & Edmonds, 2018; Langton, 2018; Santiesteban, Catmur, Hopkins, Bird, & Heyes, 2014; Wilson, Soranzo, & Bertamini, 2017). Although we suggest the PDP framework can help isolate avatar-perspective calculation as the construct of focal interest in indirect measures of L1-VPT, prior work indicates that the constructs captured by PDP parameters reflect a combination of domain-general and domain-specific processes (e.g., Payne, 2001, 2005). Thus, the current findings are silent on this debate, and we cannot rule out the possibility that the observed effects of time pressure on avatar-perspective calculation in L1-VPT are largely driven by domain-general processes.

Insofar as domain-general processes surely contribute to domain-specific phenomena, however, we concur with Michael and D'Ausilio (2015) that future work on this topic will benefit from a *complementary approach* that aims to understand how domain-general processes (e.g., attentional cueing) function in specific social contexts rather than to adjudicate between the mentalizing and sub-mentalizing interpretations of altercentric interference in L1-VPT. Adopting this complementary approach may also help elucidate the potential role of mental-rotation processes in the observed effects of time pressure on avatar-perspective calculation in L2-VPT. Identifying *how* an object looks to another agent is thought to require an embodied form of mental rotation (Kessler & Rutherford, 2010; Kessler & Thomson, 2010; Surtees et al., 2013a, 2013b), and mental rotation on its own (i.e., in the absence of perspective taking) is effortful and resource-dependent (Hyun & Luck, 2007). Thus, it is plausible that people are less likely to mentally rotate themselves into the avatar's physical position when their processing opportunity is limited, which, in turn, may result in reduced level-2 perspective calculation. Future research will be needed to test this possibility.

10. Conclusion

Insights gleaned from indirect measures of mentalizing have challenged the long-held assumption that reasoning about what other people see, know, and want requires active deliberation. In the current work, we used process-dissociation analysis to isolate perspective *calculation* in indirect measures of visual perspective taking, and we examined the efficiency of perspective calculation by limiting participants' opportunity to engage in effortful processing. Collectively, the results revealed that time pressure reduced perspective calculation in level-2, but not in level-1, visual perspective taking. These findings suggest that the process of encoding *what* objects other people can see, though not *how* they see those objects, operates even when cognitive resources are in short supply. More generally, this research highlights the utility of the process-dissociation framework as a methodological tool for increasing theoretical precision in the assessment of component cognitive processes underlying visual perspective taking.

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Appendix A. Supplementary data

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