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Level 2 Perspective Taking Entails Two Processes: Evidence From PRP Experiments

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In many situations people need to mentally adopt the (spatial) perspective of other persons, an ability that is referred to as "Level 2 perspective taking." Its underlying processes have been ascribed to mental self-rotation that can be dissociated from mental object-rotation. Recent findings suggest that perspective taking/self-rotation may not require central capacity. By using the psychological refractory period (PRP) paradigm and the locus-of-slack logic, the present study scrutinized these results, ruled out alternative explanations, and extended the conclusions. In sum, the findings converge on the notion that Level 2 perspective taking entails 2 processes: a first effortless process that handles rotations of 60° or less, and a second capacity-limited process of mental self-rotation proper that is only invoked at higher degrees of required perspective taking.

Keywords: PRP, psychological refractory period, mental rotation, perspective taking, self-rotation

The ability to adopt somebody else's perspective is an important property of cognitive development and has attracted psychologists' attention for many decades. Conceivably, everyday life frequently affords the adoption of others' perspectives. For example, verbally locating an object can, depending on the social and cultural context, be more successful and/or appropriate if done from the perspective of somebody else, in this example, the communication partner (Grabowski & Miller, 2000; Schweizer, 2003). The ability to adopt someone else's (spatial) perspective has been termed "Level 2 perspective taking"[1] (Flavell, Green, & Flavell, 1986; hereinafter abbreviated as PT) and been ascribed to mentally rotating oneself into the required position. The present study addresses the question whether PT is a capacity-limited process occupying a central bottleneck or not by using the psychological refractory period (PRP) paradigm.

PT Versus Object-Rotation

Clearly, PT and mental object-rotation (Shepard & Metzler, 1971) share several similarities superficially, yet they can be dissociated by various means. Indeed, according to the "multiple systems framework" various rotation abilities depend on (a) some general-purpose processes/abilities and (b) transformation-specific resources (Zacks & Michelon, 2005). Individual differences research also points to a dissociation of PT and object-rotation. For example, Kozhevnikov and Hegarty (2001; also Hegarty & Waller, 2004) found that only a two-factor solution was able to account for the correlations among various psychometric object-based and PT tests (although both proposed factors were not independent of each other): Object manipulation tests loaded on one factor, whereas spatial orientation or PT tests loaded on the other factor. Kessler and Thomson (2010) also showed that PT and object-rotation are differently embodied as only performance in PT tasks was affected by whole body posture (for an interaction of bodily movements and object-rotations, see also Janczyk, Pfister, Crognale, & Kunde, 2012; Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998). Additionally, both processes also seem to draw on distinct neural systems (Lambrey, Doeller, Berthoz, & Burgess, 2012; Zacks, Vettel, & Michelon, 2003).

Finally, and of most importance for the present purpose, different patterns of response time dependency on angular disparity are observed: In object-rotation tasks, response times typically increase in a linear fashion with angular disparity even at small angles (e.g., Cooper & Shepard, 1973; Shepard & Metzler, 1971). In contrast, response times in PT tasks exhibit discontinuities with little to no increases at small angles, followed by a marked increase starting at around 60°–90° of rotation (e.g., Graf, 1996; Herrmann & Graf, 1991; Herrmann, Graf, & Helmecke, 1991; Kessler & Thomson, 2010; Michelon & Zacks, 2006; Popescu & Wexler, 2012). Based on their analysis of verbal protocols, Kozhevnikov and Hegarty (2001) suggested that this pattern results from a change in strategy, and an explicit "perspective strategy"—requiring the effortful processes of transforming reference frames—was only reported for higher degrees of required PT. At small angles an "angle strategy" based on simple visual matching can be successful. A similar interpretation was advocated by Kessler and Thomson (2010), supported by their finding that embodiment effects (resulting from various body postures of the participants) were

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[1] This ability must be distinguished from "Level 1 perspective taking," meaning that somebody only can tell what another person sees but not how the world is represented from the other person's perspective (Flavell et al., 1986; see also Kessler & Rutherford, 2010).

only observed at higher degrees of required PT. To start with, the present study provides independent evidence in support of the two processes/strategies interpretation by use of a well-established chronometric approach, the PRP paradigm.

The PRP Paradigm and the Locus-of-Slack Logic

In a PRP experiment each trial comprises two different tasks, i.e., Task 1 and Task 2. The two imperative stimuli (S1 and S2) are presented in rapid succession with a varying stimulus onset asynchrony (SOA) and each task requires a separate response (R1 and R2). While response times to Task 1 (RT1) are barely if at all affected by the SOA variation, response times to Task 2 (RT2) increase when SOA decreases. This *PRP effect* is robust across numerous experimental variations using an assortment of different tasks. Only a few, and still controversial, exceptions have been reported (for overviews, see Janczyk, Pfister, Wallmeier, & Kunde, 2013, and Lien, Ruthruff, & Johnston, 2006). Several models have been advanced to explain the PRP effect, most notably structural or strategic central bottleneck models (Meyer & Kieras, 1997; Pashler, 1984, 1994; Smith, 1967; Welford, 1952), and graded capacity sharing models (Navon & Miller, 2002; Tombu & Jolicoeur, 2003). In the present study I assume a central bottleneck because the critical predictions are essentially the same for the different models, yet a central bottleneck model appears to be the most parsimonious one. Furthermore, it has been assumed in other studies for similar purposes. Therefore, a more detailed discussion of its assumptions and consequences is provided in the following section.

Processing of a given task is typically divided into three stages (see Figure 1a for the following explanations): precentral (A; e.g., perceptual encoding), central (B), and postcentral (C; e.g., motor execution). The core assumption of central bottleneck models is that at any time only one central stage can be processed, hence the bottleneck. In contrast, pre- and postcentral stages can proceed in parallel with other stages. If the two tasks are to be processed in close succession (i.e., with a short SOA), Stage A of Task 2 (A2 in Figure 1a) finishes before the bottleneck is released from central processing of Task 1 (B1 in Figure 1a). Therefore, central processing of Task 2 (B2 in Figure 1a) is postponed until the bottleneck is available (i.e., until after processing of B1 is finished). The idle time from finishing A2 to starting B2 is called the *cognitive slack* (Schweickert, 1978). In sum, RT2 at short SOAs is long. With a long SOA, however, processing of A2 necessarily starts later and no (or a smaller) cognitive slack emerges, yielding a faster RT2.

The *locus-of-slack logic* (Schweickert, 1978; see also Miller & Reynolds, 2003, for a summary) can be used to identify whether a manipulation implemented in Task 2 affects the precentral or a later processing stage. Assume now that a manipulation *M* prolongs the central stage of Task 2 (B2) with an amount of time *m*. This situation is illustrated in Figure 1b, with *M* being visualized by the dashed box. In this case, RT2 is longer at short *and* long SOAs by the same amount, *m*, producing an additive effect of SOA and *M* (see Figure 2a). A variety of manipulations have been shown to combine additively with SOA, thus having bottleneck properties, e.g., the number of S-R mappings, (explicit) memory retrieval (Carrier & Pashler, 1995), endogenous action effect activation (Paelecke & Kunde,

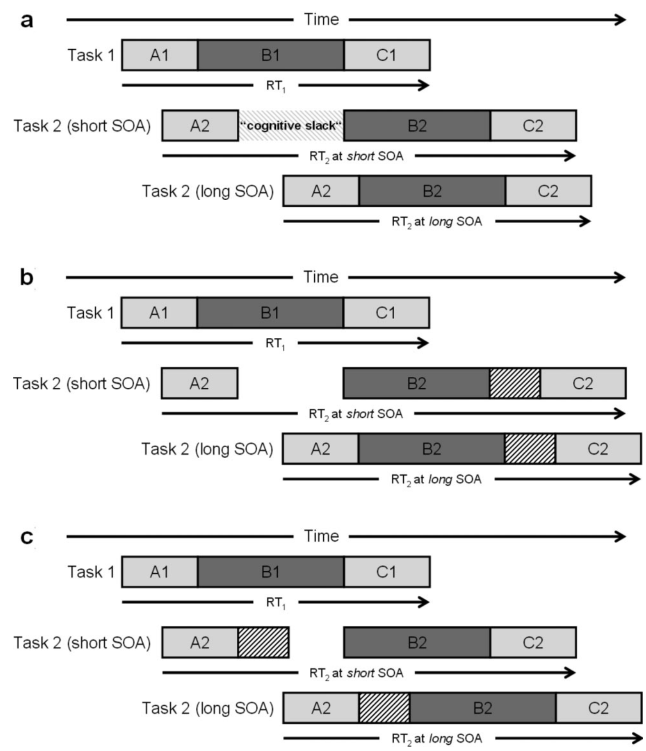

Figure 1. Illustration of a psychological refractory period experiment assuming a (structural) central bottleneck. (a) Processing of Tasks 1 and 2 without experimental manipulations except for stimulus onset asynchrony (SOA). (b) Processing of Tasks 1 and 2 with a manipulation implemented in the central stage of Task 2. (c) Processing of Tasks 1 and 2 with a manipulation implemented in the precentral stage of Task 2. A = precentral stage; B = central stage; C = postcentral stage; RT = response time.

2007), or the processing of tool-transformations (Kunde, Pfister, & Janczyk, 2012). Now assume that *M* instead affects the precentral stage of Task 2 (A2; see Figure 1c). At short SOAs the additional demand of *M* is processed while the bottleneck is still occupied by Task 1: *M* is absorbed into the slack and RT2 is not prolonged (as in Figure 1a). At long SOAs, in contrast, when no (or a smaller) slack exists, stage B2 must be postponed until after A2 is finished. This prolongs RT2 with an increasing SOA resulting in an underadditive interaction of SOA and *M* (see Figure 2b). Manipulations of stimulus intensity or contrast that affect the perceptual characteristics of stimuli have been shown to reliably combine underadditively with SOA (Pashler, 1984; Pashler & Johnston, 1989).

Do PT and Object-Rotation Require Central Capacity?

Several PRP studies used a mental object-rotation task as Task 2; most often this was the mirror-normal judgment task (Cooper & Shepard, 1973). The stimuli's degree of orientation away from the upright position in some cases combined slightly but significantly underadditively with SOA (e.g., Ruthruff, Miller, & Lachmann, 1995, Experiment 4; Van Selst & Jolicoeur, 1994). Therefore, RT differences between the various orientations were smaller at the

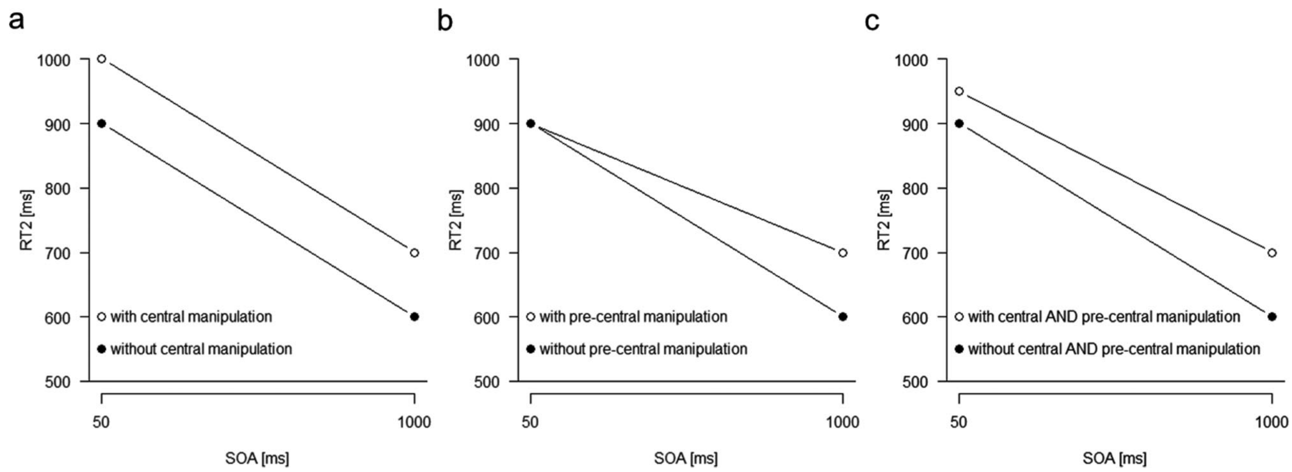

Figure 2. Expected RT2 patterns resulting from manipulations affecting (a) the central stage of Task 2, (b) the precentral stage of Task 2, or (c) both in a confounded manner (i.e., in one condition both the central and the precentral stage are affected). RT2 = response times to Task 2; SOA = stimulus onset asynchrony.

short SOA compared to the long SOAs; however, the orientation effect was not completely absent, even at the shortest SOA in these experiments. In other cases additive combinations of orientation and SOA were found (Ruthruff et al., 1995, Experiments 1–3; see also Lachmann, Schumacher, & van Leeuwen, 2009); Heil, Wahl, and Herbst (1999) found underadditivity only for high rotation angles. Based on a comparison with results from stochastic simulations, Ruthruff et al. (1995) concluded that "there seems at present very little reason to suspect that any mental rotation is carried out while the bottleneck mechanism is occupied with Task 1" (p. 568). Thus, although results are a bit mixed, some authors concluded that mental object-rotation has bottleneck properties and requires central capacity.

One might suspect that it follows that PT likely requires central capacity as well. However, I have outlined above that object-rotation and PT are dissociable, leaving the possibility that PT behaves differently. A recent study using the PRP paradigm shed some light on this particular question (Franz, Sebastian, Hust, & Norris, 2008). In the critical experiments, Task 2 required participants to judge whether they see a left or a right hand and/or arm. Stimuli in this task were pictures of hands and/or arms taken from the direct viewer perspective (requiring no PT, 0°, "direct framework") or from the opposite perspective (requiring a 180° rotation, "translated framework"). The authors observed an underadditive combination of SOA and PT which was generalized to noneffector stimuli in another experiment. In both experiments, however, there was a strong residual effect of orientation with the short SOA; that is, even at this SOA, RT2 was slower for the 180° condition compared to the 0° condition (see also Figure 2c for an illustration). In contrast to what has been concluded from similar results for mental object-rotation (Ruthruff et al., 1995, Experiment 4; Van Selst & Jolicoeur, 1994), Franz and her colleagues concluded that PT starts before the central bottleneck, hence not requiring central capacity. Note that they also acknowledge and discuss some explanations of the residual effect of orientation at the short SOA.

The Present Experiments

Given the ubiquity of capacity limitations in cognitive processing, the suggestion that PT escapes such limitations and potentially runs in parallel with other central stages is particularly interesting and noteworthy (Franz et al., 2008). However, there are at least three scenarios yielding results as those observed by Franz et al. (2008), and consequently, at present, some caution is warranted with regard to a trustworthy interpretation:

- First, an underadditive interaction with a residual effect at the short SOA (see Figure 2c) may be due to stimuli confounding perceptual and central demands. In particular, if the 180° rotated stimulus not only prolongs the central stage but the precentral, perceptual stage as well, the reported pattern is easily explained. Although the natural stimuli used by Franz et al. are clearly welcome, it is difficult to exclude that they did not vary in their perceptual demands (e.g., brightness), which in turn could be the sole reason for the particular finding.
- Second, PT may in fact run in parallel with other stages. As a consequence, the reported pattern would be explained by a cognitive slack that is too short to fully absorb the effect. This scenario was already discussed by Franz et al. (2008). According to a straightforward prediction, the residual orientation effect at the shortest SOA should disappear with shorter rotation times, i.e., by using stimuli with smaller orientations. However, this appears difficult to realize with the natural stimuli.
- Third, PT may involve two distinct strategies/processes. Franz et al. (2008) have similarly suggested that "a number of subprocesses constitute what we are referring collectively to as *spatial translation*" (p. 411, italics in original). For example, Kozhevnikov and Hegarty (2001) suggested that participants use an "angle strategy" for lower rotation degrees and a "perspective strategy" only for higher degrees. Similarly, Kessler and Thomson (2010) suggested that a "simple visual matching process could be performed at low angles" (p. 75). Hence, it is conceivable that one process or strategy copes with rotations up to approximately 60°; self-rotation proper (conceived as the cognitive transformation of

a frame of reference) is only invoked for rotations exceeding this limit. If the former is precentral and can run in parallel with other stages, while self-rotation proper is a central bottleneck process, a pattern as observed by Franz et al. (2008; see also Figure 2c) would emerge. A similar reasoning has also been advocated by Klapötke, Krüger, and Mattler (2011) in the case of unconscious priming (see also Miller & Reynolds, 2003).

The experiments reported in the present article were designed as a step toward distinguishing between these accounts. To this end, I employed schematic figures as stimuli that did not differ on factors potentially affecting precentral, perceptual processing. Experiment 1 replicates the typical RT discontinuity for PT between 60° and 90° of rotation. The remaining Experiments 2–4 are PRP experiments aimed at ruling out and distinguishing between the accounts just mentioned.

Experiment 1

To exclude that perceptual differences in terms of the stimuli's brightness or contrast yielded the underadditivity in the study by Franz et al. (2008) a replication of these results with stimuli without such differences is necessary. Hence, in the present experiments I employed schematic stimuli used in previous studies on PT (Graf, 1996; Herrmann et al., 1991; see also Kessler & Thomson, 2010, for similar stimuli). For example, stimuli displayed in Figure 3a and 3b correspond to the "direct framework" (0°) and the "translated framework" (180°) in the Franz et al. study, respectively. Figure 3c illustrates a 120° (counterclockwise) orientation. The participants' task was to imagine themselves in the position of a symbolized card-player and to indicate in which hand the player holds the cards (the small black dot at the end of the schematic arms). I expected to find an RT discontinuity at around 60°–90° of PT, demonstrating that the present setup likely requires PT (see introduction for this behavioral difference to object-rotation).

Method

Participants. Sixteen undergraduate students from Dortmund University of Technology (Dortmund, Germany) participated in this experiment (13 female; mean age: 24.3 years; range: 20–26 years; one left-handed) in exchange for course credit. Participants were naïve regarding the hypotheses underlying this experiment and reported normal or corrected-to-normal vision.

Apparatus and stimuli. A standard IBM-compatible PC was used for stimulus presentation and response recording. Stimuli were presented on a white background via a 17-in. (43.18-cm) monitor and were rotated from 0° to 330° in 30° increments (see Figure 3a–3c for examples showing 0°, 180°, and 120° orientations). Responses were given with the right middle and index finger on two external response keys.

Design and procedure. Participants were tested individually in one single session of about 30 min. Written instructions emphasized speed and accuracy. Instructions included a painting of a table with four card-players. An additional fifth person was drawn behind the card-player sitting at the nearest position (with his back to the observer). This painting was used as a further explanation of the task, i.e., that participants were to imagine themselves in the respective card-player positions indicated by the stimuli, and judge from this view whether the cards are in the left (index finger response) or in the right hand (middle finger response).

A trial began with a central fixation cross (500 ms), which was followed by the imperative stimulus, remaining on the screen until a response was registered. If no response was given within 4,000 ms or in the case of an incorrect response, an error message was shown for 1,000 ms. After a period of 1,000 ms, the next trial began. An unanalyzed practice block was followed by six experimental blocks (all 48 trials). Blocks were separated by a break of 30 s. Within each block the 24 trial types resulting from 2 response requirements (left vs. right) × 12 orientations appeared twice in a random order.

Data treatment and analyses. Equal stimulus orientations clockwise and counterclockwise (e.g., 30° and 330° or 60° and 300°) were collapsed, as in preliminary analyses "direction" had no main effect and did not interact with stimulus orientation. Thus, the resulting factor "stimulus orientation" had seven levels (0°, 30°, 60°, 90°, 120°, 150°, and 180°). For RT analyses only correct trials were considered, and RTs deviating from the mean more than 2.5 standard deviations (calculated separately for each participant and design cell) were excluded as outliers (2.7%). Mean RTs and mean error percentages were then submitted to an analysis of variance (ANOVA) with stimulus orientation as a within-subject factor. I adopted a significance level of $\alpha = .05$, and sample effect sizes are reported as η_p^2 or Cohen's d (in the case of t-tests). If necessary, Greenhouse-Geisser corrections were used; in these cases I report uncorrected degrees of freedom for clarity supplemented by the respective ε–estimate.

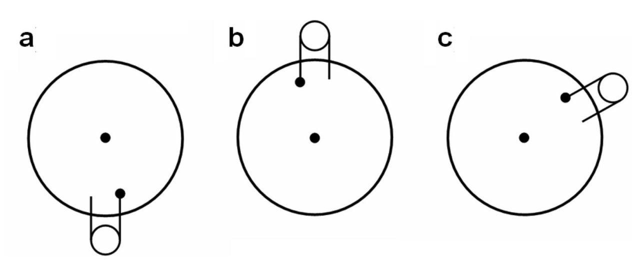

Figure 3. Examples of the stimuli used throughout the present study: Each example symbolizes a (round) table and a "card player" as seen from above. The participants' task was to indicate in which hand the card player holds the cards (the solid circle; in the right hand in each of the examples). Assuming that a potential observer is located in the "south-position," the examples require (a) 0°, (b) 180°, and (c) 120° Level 2 perspective taking (PT).

Results and Discussion

Mean RTs are visualized in Figure 4 and show the expected discontinuity between 60° and 90°: While the curve is relatively flat up to 60°, a marked and almost linear increase is observed from 60° to 180° and the ANOVA yielded a significant effect, $F(6, 90) = 29.14$, $p < .001$, $\eta_p^2 = .66$, $\varepsilon = .43$. An additional ANOVA using only the orientations from 0° to 60° indicated no significant linear trend, $F(1, 15) = 2.65$, $p = .124$, $\eta_p^2 = .15$, while this was true when only the orientations from 90° to 180° were analyzed, $F(1, 15) = 33.96$, $p < .001$, $\eta_p^2 = .69$. Mean error percentages were 2.08, 0.78, 1.17, 3.65, 8.07, 10.94, and 13.02 for the orientations of 0°, 30°, 60°, 90°, 120°, 150°, and 180°, respectively. In

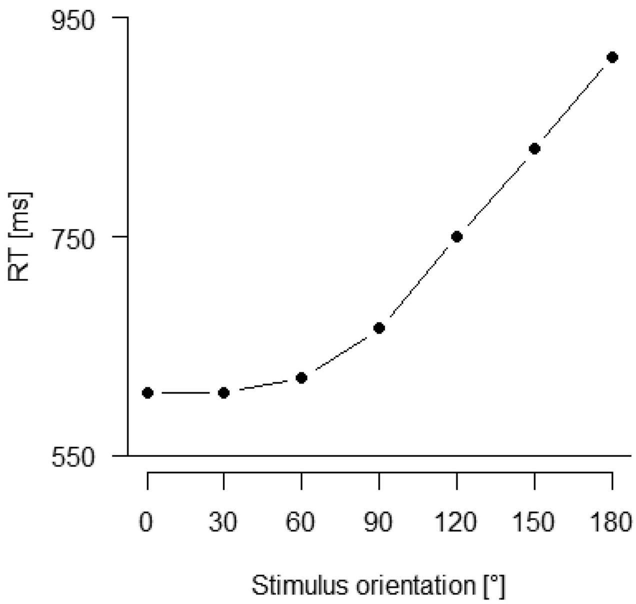

Figure 4. Response times (RTs, in milliseconds) in Experiment 1 as a function of stimulus orientation.

general, this pattern is similar to the one found for RTs, and the ANOVA was significant, $F(6, 90) = 11.35$, $p < .001$, $\eta_p^2 = .43$, $\varepsilon = .32$.

In sum, the results show the typical discontinuity observed for PT: A relatively flat trend for orientations from 0°–60° was followed by a linear increase of RTs with orientations from 90°–180° (e.g., Graf, 1996; Herrmann & Graf, 1991; Herrmann et al., 1991; Kessler & Thomson, 2010; Popescu & Wexler, 2012). Thus, the employed task and schematic stimuli appear to capture PT and were subsequently embedded in PRP experiments to further investigate the three alternative hypotheses outlined in the introduction.

Experiment 2

The PRP experiments by Franz et al. (2008) resulted in an underadditive combination of SOA and stimulus orientation, with a residual effect of stimulus orientation at the shortest SOA (see Figure 2c for an illustration). As outlined in the introduction, an alternative explanation is that self-rotation is a true bottleneck process, but the 180° oriented stimuli placed some additional burden on precentral (perceptual) processing. Such a confound might indeed be an undesired byproduct of the natural stimuli and cannot be excluded with certainty. Experiment 2 aimed at clarifying whether similar results are obtained with the PT stimuli from Experiment 1 that do not differ in terms of brightness or contrast, i.e., features affecting the precentral, perceptual stage of processing (admittedly coming at the expense of the stimuli's naturalness). To this end, in a PRP experiment I combined binary tone discrimination as Task 1 with a PT task using the same schematic stimuli as in Experiment 1 (only 0° and 180° orientations) as Task 2.

Method

Participants. Twenty undergraduate students from Dortmund University of Technology (Dortmund, Germany) participated in this experiment (16 female; mean age: 23.8 years; range: 19–35 years; one left-handed) in exchange for course credit. Participants were naïve regarding the hypotheses underlying this experiment and reported normal or corrected-to-normal vision.

Apparatus and stimuli. For stimulus presentation and response recording, a standard IBM-compatible PC was used. Task 1 stimuli (S1) were two tones (300 and 900 Hz, 50 ms, presented via loudspeakers) and responses (R1) were vocal ("tipp" or "topp"). The respective RT1 was measured by a voice key, and the response identity was registered by the experimenter. Task 2 stimuli (S2) were as in Experiment 1 (only 0° vs. 180° orientation; see Figure 3a and 3b for examples) and were presented on a white background via a 17-in. (43.18-cm) monitor. Responses (R2) were given with the right middle and index finger via external response keys.

Design and procedure. Participants were tested individually in one single session of about 45 min. Instructions were similar to those in Experiment 1; in addition, priority was given to Task 1 over Task 2.

A central fixation cross (500 ms) was followed by a blank screen (500 ms), after which S1 was played. Following an SOA of either 50 or 1,000 ms, S2 was presented and remained on the screen until R2 was given. A trial was canceled if R2 was not given within 4,000 ms, if R2 preceded R1, or if R2 was given prior to S2 onset. Erroneous trials were followed by an error message (1,500 ms). The next trial started after a fixed interval of 1,000 ms. An unanalyzed practice block was followed by five experimental blocks (all 48 trials). Blocks were separated by a minimum break of 30 s, and participants were free to take a longer break if desired.

The S-R mapping of Task 1 was counterbalanced across participants. Within each block, the 16 trial types resulting from 2 S1 (300 vs. 900 Hz) × 2 R2 (left vs. right) × 2 S2 orientations (0° vs. 180°) × 2 SOAs (50 vs. 1,000 ms) appeared thrice in a random order.

Data treatment and analyses. In general, analyses were done as described for Experiment 1, and 2.7% and 3.3% of the trials in Tasks 1 and 2, respectively, were excluded as outliers. Mean RTs and mean percentages of errors were then submitted to a 2 × 2 ANOVA with SOA and S2 orientation as within-subject factors.

Results

Task 2. Mean RTs are illustrated in Figure 5 (left panel). First, RTs were faster at the long compared to the short SOA, the PRP effect, $F(1, 19) = 126.10$, $p < .001$, $\eta_p^2 = .87$. Second, RTs to the 180° rotated S2s were slower than those to the unrotated (0°) S2s, $F(1, 19) = 30.80$, $p < .001$, $\eta_p^2 = .62$. Most important, the S2 Orientation × SOA interaction reached significance such that the difference between the 0° and 180° S2 orientation was smaller at the short than at the long SOA, $F(1, 19) = 11.16$, $p = .003$, $\eta_p^2 = .37$. However, the difference at the short SOA itself was significant as well, $t(19) = 4.07$, $p < .001$, $d = 1.29$. Error percentages are summarized in Table 1 and were overall slightly higher at the short SOA and with 180° rotated S2s. However, neither of the main effects reached significance, SOA: $F(1, 19) = 1.81$, $p = .195$, $\eta_p^2 = .09$, S2 orientation: $F(1, 19) = 2.90$, $p = .105$, $\eta_p^2 = .13$, and the same was true for the interaction, $F(1, 19) = 1.49$, $p = .237$, $\eta_p^2 = .07$.

Task 1. Mean RTs are summarized in Table 1 and were relatively unaffected by the manipulations. Accordingly, neither of

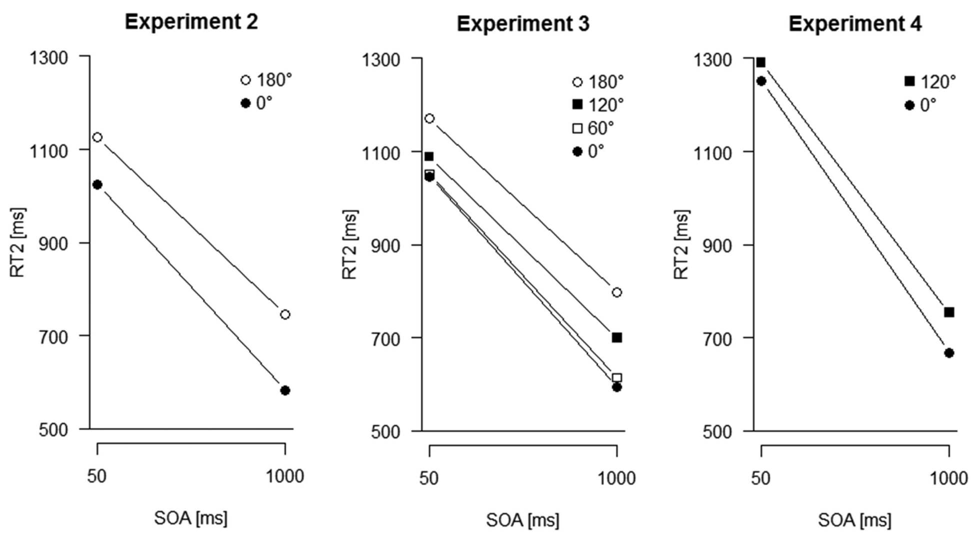

Figure 5. Task 2 response times (RT2; in milliseconds) in Experiments 2–4 as a function of stimulus onset asynchrony (SOA) and Stimulus 2 orientation.

the two main effects reached significance, SOA: $F(1, 19) = 2.02$, $p = .172$, $\eta_p^2 = .10$, S2 orientation: $F(1, 19) = 0.04$, $p = .836$, $\eta_p^2 < .01$, nor did the interaction, $F(1, 19) = 0.61$, $p = .445$, $\eta_p^2 = .03$. With unrotated S2s, participants made more errors at the short rather than at the long SOA; however, the opposite was true for the 180° rotated S2s, yielding a significant interaction, $F(1, 19) = 6.43$, $p = .020$, $\eta_p^2 = .25$. The two main effects were not significant, SOA: $F(1, 19) = 0.06$, $p = .802$, $\eta_p^2 < .01$, S2 orientation: $F(1, 19) = 0.43$, $p = .519$, $\eta_p^2 = .02$.

Discussion

The results from Experiment 2 are straightforward. Aside from an unsurprising PRP effect, the theoretically interesting pattern relates to the underadditive combination of SOA and S2 orientation with a residual effect of orientation at the short SOA. This pattern is exactly what has been reported by Franz et al. (2008). Thus, a potential confound of additional central and perceptual demands imposed by the 180° oriented stimuli in the Franz et al. study can be excluded. The following experiments focused on the second and third alternative account laid out in the introduction.

Table 1
Mean RTs of Task 1 (RT1, in Milliseconds) and Mean Error Percentages of Tasks 1 (PE1) and 2 (PE2) From Experiments 2–4 as a Function of SOA and S2 Orientation

	RT1		PE1		PE2	
	SOA (ms)		SOA (ms)		SOA (ms)	
S2 orientation	50	1,000	50	1,000	50	1,000
Experiment 2						
0°	845	828	1.82	1.09	2.09	0.67
180°	849	825	1.04	1.52	2.15	2.37
Experiment 3						
0°	896	885	2.77	1.39	0.63	0.10
60°	884	891	2.25	0.91	0.26	0.15
120°	889	892	1.72	1.28	1.38	2.92
180°	913	880	1.68	0.90	3.13	4.37
Experiment 4						
0°	1,083	1,189	4.72	4.28	1.11	0.41
120°	1,085	1,181	4.95	4.16	2.64	5.31

Note. RT = response time; SOA = stimulus onset asynchrony; S2 orientation = Stimulus 2 orientation.

Experiment 3

Having ruled out the first account presented in the introduction, the remaining two alternatives consider (a) a slack-time too short to absorb the whole precentral processing and (b) the possibility that PT consists of separate stages, the first running in parallel with other processes, the second being subject to the central bottleneck. According to the first alternative, the residual effect at the short SOA should be eliminated when a bottleneck process of PT requires less time, hence allowing for a full absorption into slack. In Experiment 3, I consequently introduced intermediate S2 orientations of 60° and 120°.

Method

Participants. Thirty-two undergraduate students from Dortmund University of Technology (Dortmund, Germany) participated in this experiment (24 female; mean age: 24.2 years; range: 20–31 years; three left-handed) in exchange for course credit. Participants were naïve regarding the hypotheses underlying this experiment and reported normal or corrected-to-normal vision.

Apparatus, stimuli, design, procedure, data treatment, and analyses. Experiment 3 was similar to Experiment 2 with few exceptions: Most important, intermediate stimulus orientations in Task 2 were introduced. Thus, stimuli were presented showing rotations of 0°, 60°, 120°, 180°, 240°, and 300°. As a consequence, each block now comprised 96 trials, with the 48 trial types resulting from 2 S1 (300 vs. 900 Hz) × 2 R2 (left vs. right) × 6 S2 orientations (0°, 60°, 120°, 180°, 240°, and 300°) × 2 SOA (50 vs.

1,000 ms) appearing twice in a random order. As in Experiment 1, equal S2 orientations clockwise and counterclockwise were collapsed (e.g., 60° and 300°) for statistical analyses, yielding four levels of the factor S2 orientation. A total of 2.9% and 3.0% of the trials in Task 1 and 2, respectively, were excluded as outliers.

Results

Task 2. Mean RTs are illustrated in Figure 5 (middle panel). First, they showed the typical decrease with an increasing SOA, thus a PRP effect, $F(1, 31) = 142.10$, $p < .001$, $\eta_p^2 = .82$. Second, they increased with increasing S2 orientations, $F(3, 93) = 66.56$, $p < .001$, $\eta_p^2 = .68$, $\varepsilon = .51$. This increase was smaller at the short than at the long SOA, as reflected by the underadditive interaction, $F(3, 93) = 7.87$, $p = .001$, $\eta_p^2 = .20$, $\varepsilon = .60$. At the short SOA, the comparison with the 0° S2 orientation condition was significantly different for the 120° S2 orientation, $t(31) = 4.37$, $p < .001$, $d = 1.09$, and for the 180° S2 orientation, $t(31) = 5.87$, $p < .001$, $d = 1.47$. For the 60° S2 orientation it was not significant, $t(31) = 0.74$, $p = .232$, $d = 0.19$. Still, this latter comparison was significant at the long SOA, $t(31) = 2.99$, $p = .003$, $d = 0.75$.

Errors (see Table 1) increased with an increasing S2 orientation, $F(3, 93) = 17.84$, $p < .001$, $\eta_p^2 = .37$, $\varepsilon = .71$, but were not affected by SOA, $F(1, 31) = 2.49$, $p = .125$, $\eta_p^2 = .07$. The interaction was significant, however, with no systematic pattern, $F(3, 93) = 3.58$, $p = .026$, $\eta_p^2 = .10$, $\varepsilon = .80$.

Task 1. Mean RTs are summarized in Table 1. Overall, they were neither affected by the SOA manipulation, $F(1, 31) = 0.18$, $p = .673$, $\eta_p^2 = .01$, nor by S2 orientation, $F(3, 93) = 1.05$, $p = .373$, $\eta_p^2 = .03$. The unsystematic interaction was significant, however, $F(3, 93) = 4.97$, $p = .012$, $\eta_p^2 = .14$, $\varepsilon = .61$. Error percentages are given in Table 1 and were higher with the short compared to the long SOA, $F(1, 31) = 14.82$, $p = .001$, $\eta_p^2 = .32$. The effect of S2 orientation was not significant, $F(3, 93) = 1.53$, $p = .213$, $\eta_p^2 = .05$, and the same was true for the interaction, $F(3, 93) = 1.06$, $p = .359$, $\eta_p^2 = .03$, $\varepsilon = .80$.

Discussion

Similar to Experiment 2, an underadditive interaction of S2 orientation and SOA was found. Interestingly, with only 60° of required PT no residual effect of orientation persisted at the shortest SOA. In other words, in this case I observed a complete absorption into slack—a pattern suggesting that PT indeed is not (completely) a bottleneck process but rather proceeds, at least in part, in parallel with other processes. However, the residual effect was clearly present for the 120° orientation, suggesting the implication of central stages for this and larger S2 orientations. Thus the results from this experiment yield initial evidence in support of the hypothesis designating two different processes or stages in PT. Alternatively, it may still be possible that the cognitive slack was too short to absorb the whole process for this orientation. This possibility will be investigated in Experiment 4, where I prolonged the slack time by lengthening the Task 1 central stage.

Experiment 4

In Experiment 3 the effect of the 60° S2 orientation was completely absent at the short SOA, consistent with an interpretation that PT indeed escapes the central bottleneck. Yet the effect was present at the 120° S2 orientation. If this was only due to a slack-time still too short for full absorption, it should vanish when the slack-time is lengthened. To this end, I increased central processing time in Task 1 by using three (instead of two) S1 and R1.

Method

Participants. Twenty-four undergraduate students from the University of Würzburg (Würzburg, Germany) participated in this experiment (16 female; mean age: 26.5 years; range: 20–44 years; three left-handed) in exchange for course credit. Participants were naïve regarding the hypotheses underlying this experiment and reported normal or corrected-to-normal vision.

Apparatus, stimuli, design, procedure, data treatment, and analyses. Experiment 4 was similar to the previous two experiments. The most important change relates to the fact that I used three S1 tones (300, 600, and 900 Hz; 50 ms) plus three vocal R1 (“tipp,” “tapp,” and “topp”). As S2 I used only the 0°, 120°, and 240° orientations. Thus, each block comprised 72 trials, with the 36 trial types resulting from the 3 S1 (300 vs. 600 vs. 900 Hz) × 2 R2 (left vs. right) × 3 S2 orientations (0°, 120°, and 240°) × 2 SOAs (50 vs. 1,000 ms) appearing twice in a random order. As in the previous experiment, equal orientations clockwise and counterclockwise (i.e., 120° and 240°) were collapsed for statistical analyses, leaving two levels of this factor. There was exclusion of 2.8% and 2.6% of the trials in Task 1 and 2 as outliers.

Results

Task 2. Mean RTs are visualized in Figure 5 (right panel). Again, a PRP effect was evident, i.e., RTs decreased with an increasing SOA, $F(1, 23) = 376.83$, $p < .001$, $\eta_p^2 = .94$. Further, RTs were faster for the 0° than for the 120° S2 orientation, $F(1, 23) = 39.53$, $p < .001$, $\eta_p^2 = .63$, and this difference was again smaller at the short SOA; thus, there was an underadditive interaction, $F(1, 23) = 10.51$, $p = .004$, $\eta_p^2 = .31$. The difference between the S2 orientations at the short SOA was significant in itself, $t(23) = 3.08$, $p = .003$, $d = 0.89$.

Overall, participants made more errors with the 120° rotated S2s than with the unrotated S2s (see Table 1), $F(1, 23) = 45.49$, $p < .001$, $\eta_p^2 = .66$. Though the main effect of SOA was significant as well, $F(1, 23) = 6.90$, $p = .015$, $\eta_p^2 = .23$, it was also qualified by the significant interaction, $F(1, 23) = 18.16$, $p < .001$, $\eta_p^2 = .44$: While for the unrotated S2s error percentages slightly decreased from the short to the long SOA, the opposite was true and more pronounced for the 120° rotated S2. In other words, the difference in error percentages was more pronounced at the long than at the short SOA, resembling the observed RT pattern.

Task 1. Mean RTs are summarized in Table 1. While they showed a slight increase with an increasing SOA, $F(1, 23) = 7.65$, $p = .011$, $\eta_p^2 = .25$, they were not affected by S2 orientation, $F(1, 23) = 0.36$, $p = .554$, $\eta_p^2 = .02$. The interaction was not significant as well, $F(1, 23) = 0.57$, $p = .456$, $\eta_p^2 = .02$. Error percentages are given in Table 1, and no effect reached significance, SOA: $F(1, 23) = 1.39$, $p = .250$, $\eta_p^2 = .06$, S2 orientation: $F(1, 23) = 0.03$, $p = .860$, $\eta_p^2 < .01$, interaction: $F(1, 23) = 0.09$, $p = .762$, $\eta_p^2 < .01$.

In two additional analyses, I compared the overall mean RT1 (1,135 ms) to that obtained in the previous two experiments. The comparison with Experiment 2 (mean RT1: 837 ms) was significant, $t(42) = 5.01$, $p < .001$, $d = 0.82$, and so was the comparison with Experiment 3 (mean RT1: 890 ms), $t(54) = 3.75$, $p < .001$, $d = 0.50$ (both *t*-tests were one-tailed).

Discussion

The results from this experiment are again straightforward. First, RT1 was considerably longer compared to the previous two experiments (more than 100 ms). This indicates that increasing the S1-R1 mappings had the desired effect of increasing the central stage of Task 1 and the cognitive slack was successfully lengthened. Despite this, the pattern observed for Task 2 was still the same as in the previous experiments. S2 orientations combined underadditively with SOA, but a clear residual effect of orientation was observed at the short SOA. This finding points to the fact that one part of PT may indeed run in parallel with other stages. However, this is clearly not possible for a second part, which must await release of the bottleneck from the Task 1 central stage.

General Discussion

The present study was meant to pinpoint the stage of processing responsible for PT. The underadditive combination of PT and SOA in a recent PRP study (Franz et al., 2008) points to a precentral locus, even though residual effects of stimulus orientation at the shortest SOA and possible explanations were already acknowledged by these authors. Drawing on these findings, I aimed at investigating the source of this particular pattern, thereby ruling out alternative explanations.

Two Processes in PT

As laid out in detail in the introduction, the just described pattern of results could easily be due to a confound in central and precentral, perceptual demands. In particular, it is possible that in an earlier study (Franz et al., 2008) the orientations of 0° and 180° not only differed in terms of self-rotation demands but that the particular stimuli also imposed increased perceptual demands with the latter orientation. In contrast, the stimuli used here cannot differ in terms of brightness or contrast (aspects that have been shown to affect perceptual processing; Pashler, 1984; Pashler & Johnston, 1989). Still, Experiment 2 replicated the findings of Franz et al. (2008), rendering this explanation unlikely. It is, however, possible, that the cognitive slack was too short to fully absorb an actually precentral process of PT. In Experiment 3 I introduced intermediate orientations of 60° and 120°, assuming that they require shorter PT times that potentially could be fully absorbed. Though this was true for the 60° orientation, a residual effect was still present for the 120° orientation. This pattern was the same in Experiment 4, where the cognitive slack was prolonged by lengthening the Task 1 central stage.

To summarize thus far, the results of Franz et al. (2008) were both replicated and extended. First, the use of biological stimuli seems not overly problematic as the use of the present stimuli did not change the results in general. Second, the results go further, and it appears that PT entails two distinct processes: A first process that can run in parallel with other concurrent processes and is thus not capacity-limited (i.e., a precentral process in the PRP terminology) and a second capacity-limited process requiring the central bottleneck. Assuming that the first process bridges the approximately first 60° of PT, this would explain (a) the flat RT curve up to this angle in my Experiment 1 (see also, e.g., Graf, 1996; Herrmann & Graf, 1991; Herrmann et al., 1991; Kessler & Thomson, 2010; Michelon & Zacks, 2006; Popescu & Wexler, 2012) and (b) the full underadditivity for the 60° orientation in Experiment 3. The second process likely is mental self-rotation proper, helping to bridge the remaining rotation degrees not already covered by the first process. This process, however, requires central capacity. This latter conclusion is well in line with work on mental object-rotation as reviewed in the introduction (Lachmann et al., 2009; Ruthruff et al., 1995, Experiment 4; Van Selst & Jolicoeur, 1994) and shows a commonality of both object- and self-rotation.

What is the nature of the assumed first process? Although a speculation, it might be that participants perform subtle bodily movements as a means to self-align themselves with the desired target position and base the response on a simple visual matching strategy (Kessler & Thomson, 2010). Such subtle and often not detectable movements in a PT task have recently been reported by Popescu and Wexler (2012). In early work on this topic, Herrmann and Graf (1991; see also Herrmann et al., 1991) have suggested that the degrees under consideration here (i.e., approximately 0° to 60°) correspond to what they termed the *manipulation region*: A phylogenetically old development resulting from the emergence of fine motor skills in the human hands. While this region is anatomically constrained to the lower degrees, it nonetheless allows for a fast alignment with a target orientation based on which a response could then be given.

Relations to Other Research Areas

Object-rotations and PT change different spatial reference frames. When objects are rotated, an allocentric or object-centered reference frame is changed. With PT, in contrast, an egocentric reference frame (i.e., a reference frame with the origin at or near to the observer's eyes) is altered. In their influential action-perception model, Goodale and Milner (1992; Milner & Goodale, 2006) have suggested that the ventral pathway (vision for perception) codes objects in allocentric coordinates, while the dorsal pathway (vision for action) codes objects in egocentric coordinates. This might be indicative of some commonalities between PT and dorsal pathway processing on the one hand, and object-rotation and ventral pathway processing on the other hand. It has, however, been claimed that dorsal processing proceeds automatically, thus without reliance on shared resources or processing mechanisms (e.g., Norman, 2002). Recent studies posed constraints on this claim by showing a strong PRP effect for various grasping tasks (Janczyk, Franz, & Kunde, 2010; Janczyk & Kunde, 2010; Kunde, Landgraf, Paelecke, & Kiesel, 2007). Apparently, both processing pathways seem to require access to capacity-limited central resources. These findings fit well with the present conclusion that self-rotation proper is a central and capacity-limited process.

Finally, the present study was based on a central bottleneck model (Pashler, 1984, 1994; Smith, 1967; Welford, 1952) and was not meant to validate this or alternative models, such as the graded capacity sharing model (Tombu & Jolicoeur, 2003). Can the data reported here help distinguish between these alternatives that make differing predictions not for RT2 but only for RT1? Whereas the central bottleneck model predicts no effect of SOA on RT1, the graded capacity sharing model predicts a decreasing RT1 with an increasing SOA. The data reported here is not in line with the latter prediction. In Experiments 2 and 3, no effect of SOA on RT1 was observed, but RT1 increased with an increasing SOA in Experiment 4. Admittedly, this latter finding is also not entirely compatible with the central bottleneck assumption, yet it has often been explained in terms of response grouping (e.g., Miller & Ulrich, 2008).

Conclusion

The present study followed-up a recent study on PT within the PRP paradigm (Franz et al., 2008). Briefly, this study suggested that PT could start before a central bottleneck. First, the present findings confirm these results and rule out alternative explanations. Second, the present findings go beyond that and allow the conclusion that PT entails two distinct processes: One effortless process bridging the first approximately 60°, and a second capacity-limited one required for higher rotation degrees.

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