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Dissociable mechanisms of spatial processing and decision-making on mental rotation tasks: influences from affect and motivation between genders

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By

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B.S. University of Toronto, 2017

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A dissertation submitted to the Faculty of the
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Doctor of Philosophy
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Abstract

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By Yaxin Liu

To perform well on a cognitively demanding task (i.e., mental rotation), one needs to accumulate enough evidence from the available information to increase one's likelihood of attaining the correct answer. Although the extant evidence suggests roles for affective and motivational factors on decision-making, much remains unknown about how these factors influence the performance of mentally rotating objects (mental rotation task), where robust gender performance disparities are observed. In the current dissertation, I used drift diffusion modeling (DDM) to test the extent to which the mechanisms of visuospatial information processing and decision-making are influenced by affective and motivational states. Using DDM, I examined the model parameters of processing efficiency (indexed by drift rate) and the amount of evidence accumulation (indexed by decision thresholds) to inform the mechanisms underlying individual differences on mental rotation performance. Moreover, I examined whether affective and motivational factors may shed light on the gender differences found on mental rotation tasks. Consistent with the hypotheses that affective and motivational states may differentially associate with information processing and decision-making, I found gender differences on drift rates when the mental rotation task emphasized speed over accuracy (Chapter 2). Furthermore, decision confidence uniquely mediated the link between gender differences in drift rates and decision thresholds (Chapter 3). In addition, I found that approach/avoidance states interacted with gender and affective states to differentially associate with drift rates and decision thresholds (Chapter 4). Taken together, these studies uncover the mechanisms underlying spatial processing efficiency and decision-making with respect to gender differences, providing support for the roles of affective and motivational states in visuospatial task processes.

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## Abstract

To perform well on a cognitively demanding task (i.e., mental rotation), one needs to accumulate enough evidence from the available information to increase one's likelihood of attaining the correct answer. Although the extant evidence suggests roles for affective and motivational factors on decision-making, much remains unknown about how these factors influence the performance of mentally rotating objects (mental rotation task), where robust gender performance disparities are observed. In the current dissertation, I used drift diffusion modeling (DDM) to test the extent to which the mechanisms of visuospatial information processing and decision-making are influenced by affective and motivational states. Using DDM, I examined the model parameters of processing efficiency (indexed by drift rate) and the amount of evidence accumulation (indexed by decision thresholds) to inform the mechanisms underlying individual differences on mental rotation performance. Moreover, I examined whether affective and motivational factors may shed light on the gender differences found on mental rotation tasks. Consistent with the hypotheses that affective and motivational states may differentially associate with information processing and decision-making, I found gender differences on drift rates when the mental rotation task emphasized speed over accuracy (Chapter 2). Furthermore, decision confidence uniquely mediated the link between gender differences in drift rates and decision thresholds (Chapter 3). In addition, I found that approach/avoidance states interacted with gender and affective states to differentially associate with drift rates and decision thresholds (Chapter 4). Taken together, these studies uncover the mechanisms underlying spatial processing efficiency and decision-making with respect to gender differences, providing support for the roles of affective and motivational states in visuospatial task processes.

## Chapter 1 - General Introduction

Imagine that you are assembling a piece of furniture, like a bookshelf. You may mentally turn, or flip, some pieces in the assembly instructions to figure out how the pieces fit together to create the finished product. This everyday activity involves a fundamental capacity to mentally represent and manipulate objects in three dimensions. In a seminal study investigating this process, Shepard and Metzler (1971) presented participants with 2-D depictions of 3-D objects, which could either be congruent (such that one is a rotated version the other) or incongruent (i.e., mirror images that cannot be rotated into congruence); see Figure 1 for an illustration. Participants were tasked with mentally rotating objects to decide whether the two objects were the "same" (congruent) object or "mirrored" (incongruent) versions of one another. To make these task decisions, the following stages have been proposed: (1) perceptual preprocessing; (2) discrimination of orientation; (3) rotation; (4) judgment; and (5) response execution (Heil & Rolke, 2002).

Despite the recognition of different stages of processing, numerous studies have largely examined how overall performance (e.g., accuracy) on the tasks may be influenced by a range of variables and how these effects may differ between genders. First, there are stimulus-specific factors, which include angular disparity (Coluccia & Louse, 2004), stimulus complexity (Jansen-Osmann & Heil, 2007; Titze et al., 2008), and difficulty (Prinzel & Freeman, 1995). Second, there are cognitive factors, such as working memory (Hyun & Luck, 2007; Wang & Carr, 2014), spatial attention (Corballis & Manalo, 1993), and executive function (Miyake et al., 2001). Third, there are decision-making factors such as time constraints (Voyer, 2011), task strategies (Geiser et al., 2006; Hirnstein et al., 2009), response style (Gardony et al., 2017; Pazzaglia & Moè, 2013), and task format (Glück & Fabrizii, 2010). Finally, they are social-cultural factors, such as spatial experiences (Nazareth et al., 2013), cultural (Lippa et al., 2010), educational (Peters et al., 2006), and socioeconomic background (Levine et al., 2005). Despite extensive research on these influences, a challenge remains in identifying whether these factors influence task performance at the stage of information processing, or during decision making (Provost & Heathcote, 2015). Furthermore, the magnitude of gender differences (usually favoring males) may vary as a function of these task- or decision-related factors (Peters, 2005; Voyer, 2011). Given that information and decision-stage processing are not easily dissociable based solely on behavioral performance, much remains unknown about the underlying mechanisms of different stages of processing and the factors influencing them.

### Stages of mental rotation processing are informed by computational modeling

Mental rotation is considered a continuous process of rotation that is analogous to rotational movement in the physical world. This theoretical claim is supported by ample evidence of motor simulation from both behavioral and neuroimaging studies (Menéndez Granda et al., 2022; Zacks, 2008). From a behavioral standpoint, the speed of making a same/mirror judgment changes monotonically with angular disparity, suggesting that the transformation of representation follows principles akin to those in the real world, such as the physical rotation of objects. Neural evidence supports this view, showing that the mental rotation of objects may recruit the brain regions that involve the processing of visual motion (Cohen et al., 1996).

Although much is known about how imagined rotation resembles physical rotation, less is known about the decision-stage processes that comprise a mental rotation task, wherein participants make a decision about whether two objects are the same or mirror images of one another. Questions remain because, first, there is an assumption that the mental rotation of objects is holistic, such that the entirety of an object is rotated to match the other. In this case, reaction times are attributed to the time it takes to mentally rotate the objects, while the decision time is negligible. This may not be the case, however, and further investigation into decision-stage processes is warranted. Second, and relatedly, the rotational processes and the decision-stage processes are intricately linked and, thus, these two processes may not be straightforwardly dissociable from reaction times, necessitating further research to examine both processes.

Recent research has begun to challenge the assumptions above. Studies have found that not only is holistic rotation not a prerequisite for mental rotation judgments, decision-stage processes may interfere with mental rotation (Band & Miller, 1997). For example, a variety of task strategies are applied on mental rotation tasks, with individual and gender differences in strategies (Heil & Jansen-Osmann, 2008; Toth & Campbell, 2019). Some individuals, rather than rotating objects holistically, use a piecemeal strategy, matching the parts for the two objects. Accordingly, decisions may not be based on mental rotation alone but, instead, may involve multiple sources of information that may be strategically adjusted. Additionally, the presence of non-linear reaction times when angular differences were presented in small intervals (Rossi & Collyer, 1986) and biased reaction times arising from previous stimuli (Ilan & Miller, 1994; Wong et al, 2017; Yu et al., 2020) suggest that reaction times do not reflect rotational processes only, but also take the decision-making factors of the task into account.

Indeed, despite mental rotation tasks being viewed as a sequential process in which a decision follows information processing, the rotational processes can be seen as a noisy accumulation of information from stimuli used to reach a task decision. Even prior to the rotational processes, deciding which direction to rotate the objects is perceived as choosing a series of simulations to run; the represented objects and the direction of rotations may be nosily simulated in one's mind (Hamrick et al., 2019). During mental rotation tasks, prior research has found that mental rotation requires many successive eye fixations (Just & Carpenter, 1976). This suggests that perceptual information may be noisily gathered. Additionally, successive eye fixations may also reflect various non-holistic strategies that involve frequent, and successive, decisions (Toth & Campbell, 2019).

Although dissociating information processing and decision-stage processes from analyses of accuracy and RTs is challenging, a type of sequential sampling model, known as drift diffusion modeling (DDM), provides a unique advantage in decomposing a mental rotation task into distinct stages (see Figure 1). Under this modeling framework, after the encoding of the stimulus, sensory evidence is noisily accumulated until a decision criterion is achieved (Ratcliff & McKoon, 2008). There are two primary parameters of interest[1]. The first is the drift rate, defined as the average slope of information uptake from the sensory evidence per unit time and serves as an index of the efficiency of information processing (Voss et al., 2004). The second is the decision threshold, defined as the amount of evidence that is accumulated before the execution of a decision, and serves as an index of decision strategy (Ratcliff & Rouder, 1998).

DDM offers unique advantages to decompose mental rotation. As an evidence accumulation model, it allows cognitive processes as complex as mental rotation can be broken down into elementary information processes (Simon, 1979). Additionally, this computational framework assumes that participants make strategic adjustments to make decisions optimal to the sensory evidence. In comparison with other evidence accumulation models, such as the linear ballistic accumulator (LBA), DDM produces more accurate estimates of drift rates from sensory evidence, particularly with respect to the effects of orientation (Osth et al., 2017; Provost & Heathcote, 2015).

[1] Non-decision time, defined as the time taken for perceptual encoding and motor execution of choices, can also be modeled from DDM.

The LBA assumes deterministic accumulation, involving two parallel accumulation processes for each binary choice. By contrast, DDM assumes diffusive accumulation, with a single accumulation process for two choices (Heathcote & Matzke, 2022). Thus, the information processing assumed by DDM may more closely resemble the processes entailed by mental rotation. Additionally, DDM assumes that the decision processes and information processing may be noisily accumulated and intermixed, instead of linear and sequential, as in LBA. Therefore, the DDM model allows for an exploration of possible gender differences in task performance by taking account of individual variations during the decision-making processes.

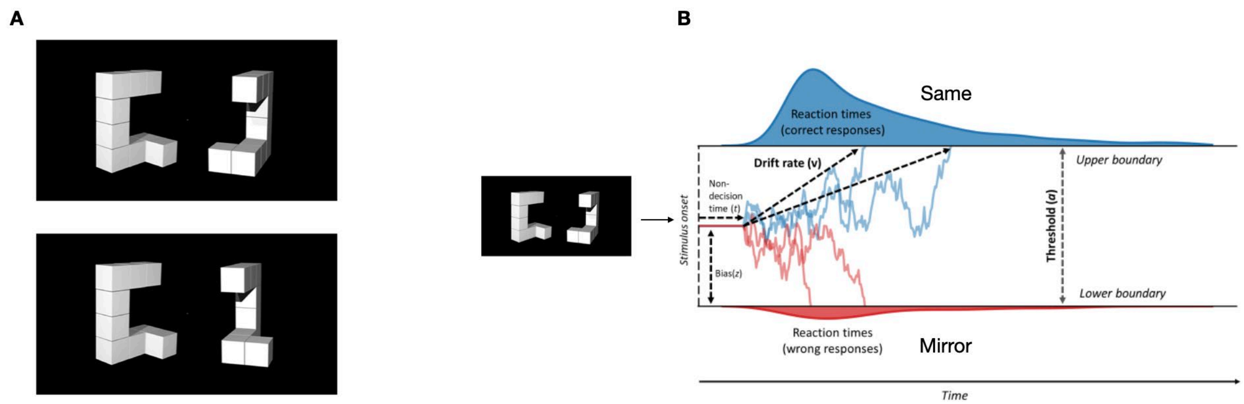



**Figure 1.** (A) Examples of same (top) and different/mirror (bottom) trials on the MRT (Ganis & Kievit, 2015). (B) Schematic illustration of the drift diffusion model. Information accumulates until a boundary is reached. Adapted from HDDM (Wiecki et al., 2013) in the context of a same trial.

**Gender differences on mental rotation tasks**

Among cognitive tasks, mental rotation tasks have consistently produced the largest gender differences in accuracy, with male participants generally outperforming female participants (Voyer et al., 1995). Intriguingly, a meta-analytic review found that a major factor influencing the magnitude of the gender differences was the amount of time constraints on the task (Voyer, 2011). Specifically, the shorter the time constraint, the larger the gender difference favoring males (Voyer, 2011).

One possibility arising from this meta-analytic review is that men and women may differ in their perceptual speed on mental rotation stimuli, and as such, time constraints affect women more than men (Voyer, 2011). However, this hypothesis remains largely unexamined, largely because rotational speed — the speed at which one mentally rotates an object—is difficult to dissociate from overall response times. Importantly, gender differences in the relation between RTs and angular disparity have produced mixed evidence. Some studies have shown gender differences in the slopes of individuals' RTs, with male participants demonstrating a steeper slope than female participants (Kail et al., 1979). Conversely, other studies have found no differences in slopes (Wiedenbauer et al., 2007). These inconsistent findings on slope differences suggest that when RTs are considered as a measurement of rotational speed, much remains unknown about the potential male advantage in information processing. Notably, even when accuracy and response times were jointly modeled (i.e., Rasch model), processing speed did not differ between men and women (Debelak et al., 2014).

The mixed results concerning response times also raise questions about the role of non-rotational processing in gender differences. Notably, gender differences have been found in the intercept of the RT function, even when slopes did not differ (Jansen & Kaltner, 2014). This suggests that decision-stage processes may contribute to these disparities (Ilan & Miller, 1994; Hooven et al., 2004). Specifically, gender differences in intercepts were found in stimuli with 0° disparity, which involves a comparison of identical pairs with no rotation (Jansen & Kaltner, 2014; Jansen-Osmann & Heil, 2007). Thus, it has been suggested that men and women may differ in the time they allocate to perceptual comparisons during decision-stage processes. Furthermore, task strategies are known to contribute to gender differences in the non-rotational aspects of mental rotation tasks (Boone & Hegarty, 2017), suggesting that information processing of mental rotation alone may not fully explain gender differences on mental rotation tasks. However, the examination of gender differences in decision-stage processes remains limited.

In summary, open questions remain about how the time pressure affects gender differences on mental rotation tasks: does it impact rotational speed (processing efficiency) and/or decision-stage mechanisms (decision threshold). And are women more impacted that men at one or more of these stages?

**Preliminary findings**

As a preliminary step in this dissertation, drift diffusion modeling was fitted to four existing datasets to test for gender differences in processing efficiency (indexed by drift rates) and the amount of evidence accumulation (indexed by decision thresholds; see Figure 2). In summary, these analyses revealed mixed findings with respect to the gender differences in these model parameters. Specifically, gender differences in drift rates, favoring males, were observed in two of the four datasets. With respect to decision thresholds, gender differences were found in three out of four datasets. Unknown, however, was whether male participants had larger decision thresholds than female participants. Altogether, the nature of the gender differences in processing efficiency and decision thresholds remains unclear. In particular, what might account for the variability across studies? And what might the relevant differences be?

As mentioned in the previous section, one possibility is the role of time constraints (Voyer et al., 2011). These time constraints could have varied across studies, yet such information about time constraints was not always available in all datasets. Thus, it remains important to examine gender differences in the model parameters in relation to time constraints. Additionally, recent research has highlighted the role of affective factors in influencing the magnitude of gender differences (for review, see Lourenco & Liu, 2023). I discuss this possibility in the next section.

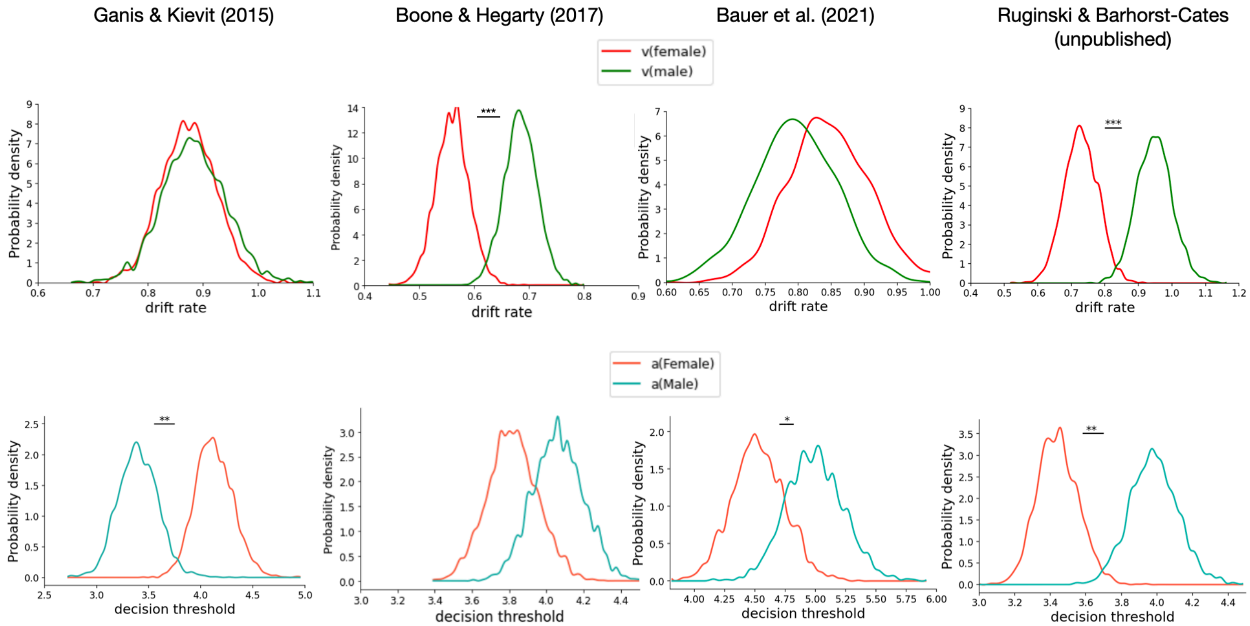



**Figure 2.** Posterior parameter values of drift rates and decision thresholds in four datasets. Dataset 1 is a publicly available dataset with 54 participants (N = 54; Ganis & Kievit, 2015). Dataset 2 comes from Experiment 2 (N = 129) of Boone and Hegarty (2017) and was obtained directly from the authors. Dataset 3 comes from Bauer et al. (2021), publicly available from the link. Only the data prior to a mindfulness intervention were used. Dataset 4 comes from a publicly available repository (N = 189) by Ruginski and Barhorst-Cates, unpublished). **posterior probability* > .95, ** *posterior probability* > .99, *** *posterior probability* > .999. See OSF link for descriptions of the datasets and modeling procedures.

## Decision uncertainty and affective states

A central insight of the DDM framework is that decisions are made under uncertainty, and both the noisy accumulation of stimulus and decision processes are subject to affective factors that influence an individual's internal state to make task decisions. Recently, significant advances have been made in understanding the integration of emotion and decision-making (Lerner et al., 2015). Many studies have shown that emotion affects the evaluation of evidence, the selection of decisions, and the evaluation of decisions (Paulus & Yu, 2012). Here, we use an umbrella term "affect" to refer to emotionally charged states (Russell, 2003). Although there is agreement about how affective states may be estimated from task processes, there is little consensus on how affective states are related to information processing and evidence accumulation (Yeung & Summerfield, 2012).

Affective states may be estimated at different steps of task processes and are associated with the evaluation of sensory evidence, during, or prior to, or even after decision-stage processes ( Meyniel et al., 2015; Mohanty et al., 2023). For example, anxiety, typically conceptualized as an anticipatory response to uncertainty, can either enhance processing (Borst et al., 2012) or impair processing (Eysenck et al., 2007; Lyons et al., 2018). Although higher anxiety drains working memory resources needed for tasks such as mental rotation, anxiety may also boost perceptual and motor processing speed, particularly on stimuli with low spatial frequency (Borst & Kosslyn, 2010). In other words, anxiety may impair information processing during the evaluation of evidence but enhance information processing prior or after the evaluation of evidence. In a similar vein, the role of anxiety in evidence accumulation is not clear-cut. Risk-aversion, which typically associates with more evidence accumulation to reduce decision error, may be associated with anxiety. Anxiety is also associated with risk-taking and impulsive decisions (e.g., less evidence accumulation) (for review, see Roberts & Hutcherson, 2019).

Confidence, defined as the degree of belief to portable events and often manifested as metacognitive judgments about one's decisions (Meyniel et al., 2015), is another important factor that relates to uncertainty. Some studies have found that confidence is positively correlated with mental rotation accuracy in both male and female participants (Cooke-Simpson & Voyer, 2007; Estes & Felker, 2012). However, few studies have examined how confidence is associated with information processing, and/or evidence accumulation.

In sum, the influences of affective states on specific component processes have begun to be considered only recently. In the spatial domain, it still remains elusive how affect is associated with processing efficiency and decision-making on mental rotation tasks. This raises central questions in the current dissertation: (1) Do affective factors influence information processing, decision-making, or both? (2) How do affective factors influence information processing and decision-making? (3) Can affective factors help to explain gender differences in information processing and decision-making?

**Present work**

The current dissertation employs computational modeling to investigate whether information processing and decision-making are influenced by affective and motivational states[2]. In Chapter 2, I investigate the impact of time constraints on processing efficiency and evidence accumulation in male and female participants. Participants either completed a mental rotation task under a task condition with a strict time limit and an emphasis on performing quickly, or a task condition that was untimed and with an emphasis on performing accurately. Gender differences in processing efficiency and evidence accumulation were examined across these conditions, providing important findings regarding the nature of time constraints on mental rotation performance.

In Chapter 3, I examined the role of affective factors in processing efficiency and evidence accumulation in male and female participants. Participants rated their levels of anxiety, confidence, and motivation in randomly selected trials. This work provides novel evidence for the associations between model parameters and each of the affective factors. It also provides evidence for how affective factors may account for gender differences in processing efficiency and evidence accumulation.

In Chapter 4, I examined how distinct motivational states (approach motivation versus avoidance motivation) interact with affective states on processing efficiency and evidence accumulation in male and female participants. This work not only provides evidence that distinct affective factors associate with individuals' processing efficiency and evidence accumulation, it also provides evidence that the influence of motivational states may interact with specific spatial processing on same versus mirror trials.

Across three studies, the current dissertation posits dissociable mechanisms of information processing and decision-making on mental rotation tasks. This work shows that these distinct stages

[2] Non-decision time ($t$) and choice bias ($z$) are not primary parameters of interests. When they are modeled, results are presented in Supplemental Information.

of processing are influenced by affective and motivational states, and provide novel insights into the gender differences on mental rotation tasks.

## Chapter 2 - Gender differences on mental rotation tasks emphasizing speed over accuracy

Task performance often depends on a balance between speed and accuracy, generally referred to as the 'speed-accuracy tradeoff' (Bogacz et al., 2010). This tradeoff arises because gathering relevant information for a decision takes time, which may vary across tasks, and which is often limited. The impact of the speed-accuracy tradeoff on information processing is well known (Swanson & Briggs, 1969), particularly when speeded judgments are required. Under time pressure, decisions are more error prone because of changes in response thresholds (see Bogacz et al., 2010).

Interestingly, time pressure may not only affect perceptual decisions, but it may also modulate the magnitude of the gender differences, when they exist. On mental rotation tasks, in which large gender differences in accuracy are observed (Peters et al., 1995), a meta-analytic review of 36 effect sizes demonstrated that the gender differences in performance increased linearly as a function of time constraints (Voyer, 2011). In particular, female participants perform worse than male participants as time pressure increases. Indeed, the data suggest that gender differences on mental rotation tasks are smaller when time pressures are minimal (Goldstein et al., 1990).

Why might time pressure affect the gender differences on mental rotation tasks? It has been suggested that female participants adopt different strategies than male participants, which the speed-accuracy tradeoff might exaggerate. Different studies have found that women attempt to answer fewer test items than do men (Adam, 1999; Goldstein et al., 1990; Kerkman et al., 2000), which has been interpretated as a more cautious response strategy because of a lowered willingness to guess, especially on difficult items.

On untimed mental rotation tasks, it has also been found that women, but not men, exhibited a speed-accuracy tradeoff with increased task difficulty (Prinzel & Freeman, 1995; but see, Peters, 2005). More specifically, women, compared to men, showed longer RTs, but only on more difficult items. Because women and men achieved the same level of accuracy, it suggests that longer RTs were necessary to compensate for potential differences in accuracy. Indeed, despite attempting fewer items, women's proportion of correct answers among the attempted items was higher than men as task became more difficult. It is possible that these gender differences arise from women, more than men, prioritizing accuracy over speed. However, gender differences of speed-accuracy tradeoff on mental rotation tasks have not been formally tested.

The use of sequential sampling models, which have been successfully applied to a wide range of perceptual tasks (Ratcliff & McKoon, 2008), may provide insights into the speed-accuracy tradeoff on mental rotation tasks. Evidence from decision-making in sequential sampling models suggests the tradeoff can be modulated by changing the decision criterion, which is based on the amount of evidence accumulating over time (Ratcliff & Smith, 2004; White et al., 2011). Previous studies using a motion coherence task found that when participants were instructed to prioritize speed over accuracy, they exhibited smaller decision thresholds (Herz et al., 2018; Zhang & Rowe, 2014). However, it has been suggested such strategic tradeoff does not impair processing efficiency (Dambacher, 2011; Ratcliff et al., 2003). In fact, time pressure has even been associated with increased perceptual processing (Hübner & Schlösser, 2010).

Other studies, however, have argued that time pressure may also impair processing efficiency (Starns et al., 2012). For example, an emphasis on speed over accuracy reduces processing efficiency on brightness discrimination (Rae et al., 2014) and flanker (Dambacher & Hübner, 2015) tasks. Conversely, an emphasis on accuracy over speed decreases processing efficiency on an orientation discrimination task (Ho et al., 2012). Thus, time pressure may extend beyond changes in decision criterion, influencing information processing. The effect of time pressure on processing efficiency may be due to a decreased attention allocation towards the stimulus (Pieters & Warlop, 1999), potentially reducing the quality of information uptake. Moreover, processing efficiency changes as a function task difficulty(Ratcliff & McKoon, 2008). Yet it remains unknown whether time pressure interacts with task difficulty to affect processing efficiency (White et al., 2011), and whether the effect of time pressure on processing efficiency varies between men and women.

To examine whether gender differences in mental rotation change as a function of time pressure, the present study assessed male and female participants' processing efficiency and decision making under either an 'accuracy-emphasis' condition or a 'speed-emphasis' condition on a chronometric mental rotation task. To this end, we used drift diffusion modeling, which has been widely applied in studying perceptual decisions under speed-accuracy tradeoff (Ratcliff & McKoon, 2008). This modeling approach has advantages in dissociating decision parameters (decision threshold) from information processing (drift rate) , while jointly accounting for both behavioral accuracy and response times[3] (RTs). Here, a steeper processing slope (drift rate) corresponds to faster processing efficiency, and larger boundary separation (decision threshold) corresponds to greater evidence accumulation before committing to a decision.

We hypothesized that participants would show larger decision thresholds in the accuracy-emphasis condition compared to the speed-emphasis condition, consistent with increased cautionary responses when accuracy is prioritized over speed. We also hypothesized that female participants would show lower drift rates and decision thresholds compared to male participants in the speed-emphasis condition, given that time constraints may increase anxiety (Ramirez et al., 2012), which has been shown to affect women more than men.

## Methods

### *Participants*

A total of 164 adults participated in this study: 84 participants (42 females; ages 18-40 years) in the accuracy-emphasis condition and 80 participants (40 females; ages 18-40 years) in the speed-emphasis condition. Participants were randomly assigned to either condition. Our sample size was informed by an a priori power analysis from an effect size of a prior study ($\eta^2$= .06; power = .08; Boone & Hegarty, 2017). All participants were recruited online via the Prolific platform and confirmed that their birth sex matched their gender identity. During pre-screening, all participants reported normal or corrected-to-normal vision and were right-handed. Procedures were approved by the IRB at Emory University.

### *Stimuli and Procedure*

Stimuli were block objects adapted from a public stimulus library (see Figure 1; Ganis & Kievit, 2015). Visual angles were adjusted based on the participant's personal computer screen. Participants were instructed to maintain eye level with their screen. The task was programmed using PsychoPy3

[3] The term response time instead of reaction time refers to the consideration of decision time in addition to reaction time to stimulus alone.

software and hosted online on Pavlovia (Peirce, 2008). In each condition, participants were presented with two objects: one on the left and one on the right. They were required to determine whether one object could be rotated to match the other. If so, they were instructed to press the 'F' key for 'same.' If not, they were instructed to press the 'J' key for 'mirror.'

In the *accuracy-emphasis* condition, participants were instructed to "respond as accurately as possible" and were given unlimited time to respond. In the *speed-emphasis* condition, participants were instructed to "respond as quickly as possible". A prompt was presented after 7500 ms without the stimulus images. Participants completed 12 practice trials with corrective feedback. There were 96 test trials, without feedback. Object pairs differed in 0°, 50°, 100°, or 150° (randomized order), with an equal number of same and different trials per angle.

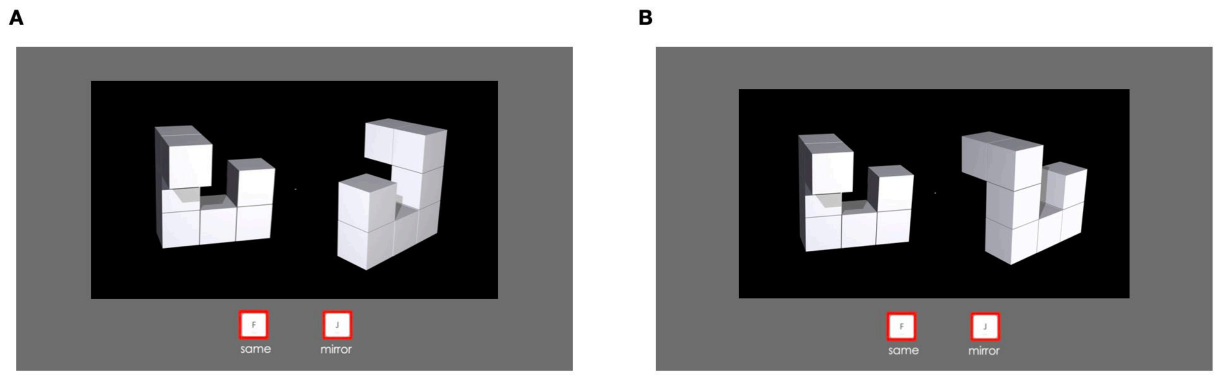



**Figure 1.** Schematic representation of the mental rotation task. A. An example of a 'same' trial. B. An example of a 'mirror' trial. Participants pressed the 'F' key indicating 'same', and the 'J' key indicating 'mirror'.

***Drift Diffusion Model (DDM)***

We modeled drift rates and decision thresholds using hierarchical drift diffusion modeling (HDDM Python 3.6; Wiecki et al., 2013)[4]. The hierarchical design of this modeling approach assumes that individual participants' model parameters, namely, drift rates and decision thresholds, are drawn from group distributions. This approach is advantageous as it optimizes both fixed- and random-effects models of individual differences.

**RT Pre-processing.** In the accuracy-emphasis condition, due to the untimed nature of the task, it was crucial to remove outliers for subsequent computational modeling. Consequently, trials with RTs exceeding 10 s were discarded (6.2% of total trials). Each participant's RTs were trimmed based on 2.5 SDs. In the speed-emphasis condition, trials with RTs exceeding the time restriction of 7.5 s were discarded (0.8% of total trials).

**Model Specification.** A simple model, in which drift rates and decision thresholds varied according to gender, was used to test for a main effect to gender. We also included a full model, in which drift rates and decision thresholds according to difficulty (angular differences: 0°, 50°, 100°, and 150°) and gender. Trial-by-trial data were inputted into HDDM for modeling, with 5% of outlier trials excluded. We used Markov chain Monte Carlo (MCMC) sampling for the Bayesian

[4] For non-decision time, see SI.

approximation of the posterior distribution of model parameters. Each model was run on 6000 samples. Our primary parameters of interest included drift rate ($v$) and decision threshold ($a$). (See SI for analyses of non-decision time [$t$.) We conducted Bayesian hypothesis testing for model parameter analysis, using 95% credible intervals. To ensure convergence, we discarded the first 200 samples (thinning = 2), and we used weakly informative priors[5] (Wiecki et al., 2013).

**Model Fit.** For each model, we used visual inspections of traces of model parameters and Gelman-Rubin statistics to assess model convergence (R-hat; Gelman & Rubin, 1992). No values exceeded 1.1, suggesting successful convergence. We implemented posterior predictive checks, in which we generated data from the posterior distributions of model parameters, for all models (see SI). The posterior predictive plots confirmed that the DDM provided a reasonable fit to the behavioral data.

## Results

### *Preliminary analyses*

**Trial type analyses.** Previous studies have found that same and mirror trials tend to diverge early in processing (Toth & Campbell, 2019). Thus, the present study analyzed the effect of trial type. A paired-samples t-test revealed that accuracy was higher on same than mirror trials in both accuracy-emphasis ($M_{\text{difference}}$= .03; $t$[83] = 2.82, $p$ = .006, 95% CI [.01, 0.05]) and speed-emphasis ($M_{\text{difference}}$= .04; $t$[79] = 2.42, $p$ = .018, 95% CI [.01, 0.06] conditions. Results also revealed that RTs were faster on same than mirror trials in both accuracy-emphasis ($M_{\text{difference}}$ = -430 ms, $t$[83] = -10.32, $p$ < .001, 95% CI [-520, -350]) and speed-emphasis ($M_{\text{difference}}$ = -150 ms, $t$[79] = -4.72, $p$ < .001, 95% CI [-210, -80]) conditions.

**Angular disparity analyses.** ANOVAs were performed to examine the effects of angular disparity on accuracy and RTs, and to test whether angular disparity interacted with trial type (i.e., same vs. mirror trials). Results revealed a significant interaction between angular disparity and trial type ($F$[1,1308] = 13.10, $p$ < .001) on accuracy. Trend analyses further revealed that the slopes were significantly steeper on same than mirror trials ($t$[1308] = -3.62, $p$ < .001; see Supplemental Figure 1). There was also a significant interaction between angular disparity and trial type on RTs ($F$[1,1308] = 30.54, $p$ < .001). Trend analyses, again, revealed that slopes were significantly steeper on same than mirror trials ($t$[1308] = 5.53, $p$ < .001; see Supplemental Figure 1).

Based on these analyses, we conducted subsequent analyses for trial type—same vs. mirror—separately. We present analyses on same trials in the main text, for consistency with other studies (Shepard & Metzler, 1971). Analyses on mirror trials, and comparisons between same and mirror trials, are available in Supplemental Information (SI).

### *Accuracy and RTs*

A linear mixed model was performed to examine the effects of condition, gender, and their interaction on the response variable (i.e., accuracy or RT), with subject as a random effect. Unless otherwise specified, we used the Satterthwaite approximation estimate degrees of freedom.

[5] Model parameters were comparable regardless of whether weakly informative priors or priors drawn from prior data were used.

Analyses of accuracy revealed a significant main effect of condition, such that accuracy was significantly higher in the accuracy-emphasis than speed-emphasis condition, $M_{\text{difference}} = .056$, $F(1, 163.54) = 6.63$, $p = .010$ (see Figure 2). The main effect of gender was also significant, $F(1, 163.54) = 4.68$, $p = .032$, such that male participants scored higher than female participants ($M_{\text{difference}} = .047$). The interaction between condition and gender was not significant, $F(1, 164) = .060$, $p = .80$. These effects replicate previous findings showing a male advantage on mental rotation tasks, but not differentially based on task instructions. Both male and female participants scored higher in the accuracy-emphasis condition compared to the speed-emphasis condition.

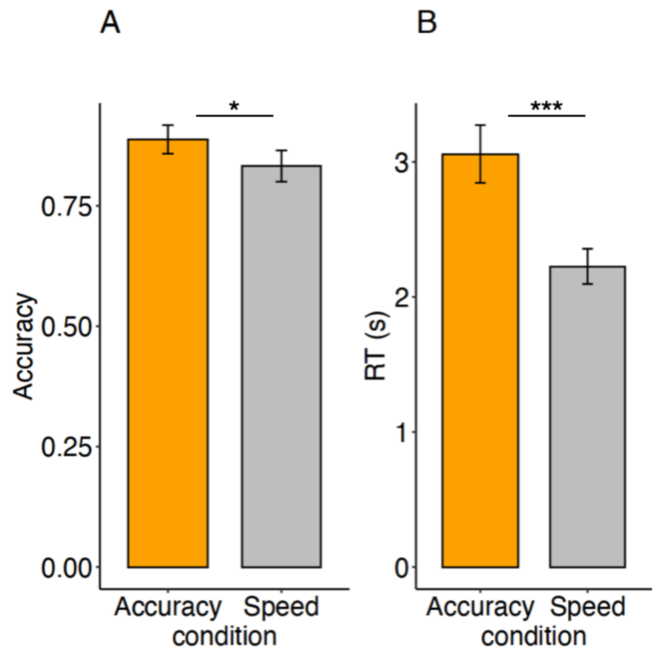



**Figure 2.** Mean accuracies and RTs in Accuracy-emphasis and Speed-emphasis conditions.
* $p < .05$, ** $p < .01$, *** $p < .001$.

Analyses of RTs revealed a significant main effect of condition, such that RTs were longer in the accuracy-emphasis than speed-emphasis condition, $F(1, 162.27) = 43.65$, $M_{\text{difference}} = 829$ ms, $p < .001$ (see Figure 2). However, there was neither an effect of gender, $F(1, 162.27) = 1.12$, $p = .291$, nor an interaction between condition and gender, $F(1, 162.27) = 0.37$, $p = .547$, for RTs. Both male and female participants took longer to respond in the accuracy-emphasis compared to the speed-emphasis condition.

### *Drift-Diffusion Modeling*

Given our hypotheses that gender differences in drift rates and decision thresholds would differ between task conditions, we allowed model parameters (drift rate, decision threshold, and non-decision time[6]) to vary as a function of gender in each condition (Model 1). Because we also speculated that gender differences might be more prominent when angular disparity was larger, we examined whether model parameters varied as a function of both gender and angular disparity (Model 2; see SI for model comparisons).

[6] See SI.

**Drift rates.** We first examined whether drift rates differed as a function of angular disparity. HDDM regression analyses revealed significant negative regression coefficients in both accuracy- and speed-emphasis conditions (> 95% posterior probabilities), suggesting that drift rates decreased as angular disparity increased in difficulty. Analyses of posterior parameter values revealed that drift rates were significantly different from each other, such that drift rates were faster for smaller than larger disparities, as expected if processing efficiency is better when task difficulty is lower (see Figure 3A).

Do drift rates differ between male and female participants across conditions and disparities? Our results revealed that gender differences differed across conditions and disparities. We compared drift rates between male and female participants in accuracy-emphasis and speed-emphasis conditions. In the accuracy-emphasis condition, group comparisons of overall drift rates collapsed across angular disparity and at each angular disparity revealed no differences between male and female participants (< 95% posterior probability; see Tables in SI). This finding suggests that men and women do not differ in their processing efficiency, at least in an accuracy-emphasis condition. In the speed-emphasis condition, however, group comparisons in drift rates collapsing across angular disparity revealed a marginal difference between male and female participants (93% posterior probability). Furthermore, a breakdown of angular disparity suggested that male participants had faster drift rates than female participants with higher angular disparities (50° and 100°: 98% posterior probabilities; see Supplemental Table 1). These findings suggest that male and female participants differ in processing efficiency when the task instructions emphasize speed, and especially on trials with medium difficulty.

Between-condition comparisons were performed to better understand how condition affected the gender differences in drift rates. Comparisons of drift rates revealed that whereas female participants showed slower drift rates in the speed-emphasis condition compared to the accuracy-emphasis condition at both 50° and 100°, male participants did not show significant differences between conditions. Furthermore, these analyses revealed that females showed significant changes in drift rates compared to male participants at 50° (95% posterior probability), but not at 100° (83% posterior probability). See Supplemental Table 2 for statistical details.

Taken together, our results reveal that gender differences in drift rates were found in the speed-emphasis condition, but not in the accuracy-emphasis condition. Specifically, whereas women showed slower drift rates in the speed-emphasis condition than the accuracy-emphasis condition, men showed no differences in drift rates across conditions. These findings suggest that women's processing efficiency may have been negatively impacted by time pressure.

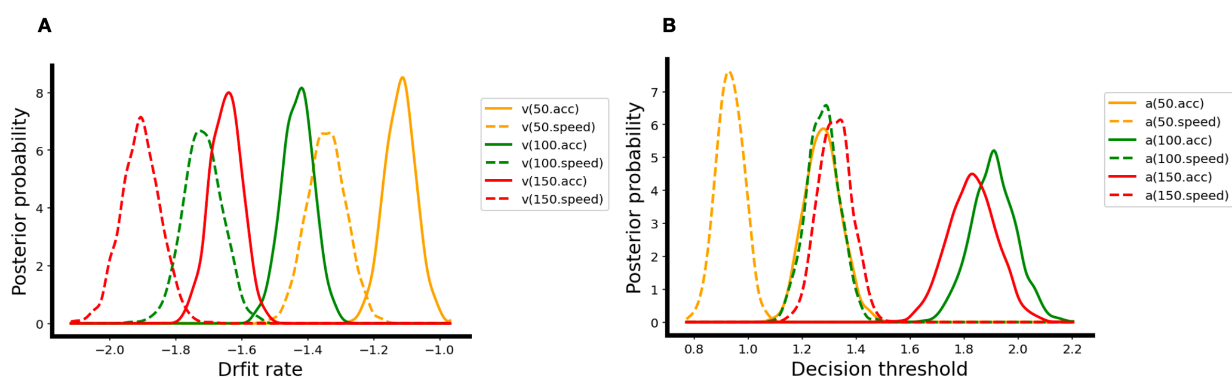



**Figure 3**. Drift rates and decision thresholds as a function of angular disparity and task condition.

**Decision thresholds.** We also examined whether decision thresholds differed as a function of angular disparity. HDDM regression analyses revealed significant positive regression coefficients in both accuracy- and speed-emphasis conditions (> 95% posterior probabilities), suggesting that decision thresholds increased as angular disparity increased. Analyses of posterior parameter values revealed that decision thresholds were significantly different from each other, such that decision thresholds were larger for larger disparities than smaller disparities, as expected if more evidence accumulation is needed when task difficulty is higher (see Figure 3B).

Do decision thresholds differ between male and female participants across conditions and angular disparities? Our results revealed that gender differences differed across conditions and angular disparities. We then compared decision thresholds between male and female participants in accuracy-emphasis and speed-emphasis conditions. In the accuracy-emphasis condition, group comparisons of overall decision thresholds collapsing across angular disparity (82.46% posterior probability), as well as at each disparity separately, revealed no differences between male and female participants (< 95% posterior probabilities; see tables in SI). These findings suggest similar levels of evidence accumulation and, thus, comparable levels of response caution in the accuracy-emphasis condition for men and women. By contrast, in the speed-emphasis condition, female participants exhibited smaller decision thresholds than male participants (98% posterior probability) when disparities were collapsed. Furthermore, we found that such gender differences were largely driven by disparities with medium and high difficulties. Female participants exhibited significantly smaller decision thresholds than male participants at all disparities except 0° (> 95% posterior probabilities; see SI). These findings suggest that female participants accumulated less evidence and exhibited less caution than male participants in the speed-emphasis, but not accuracy-emphasis, condition.

Between-condition comparisons were performed to better understand how the condition manipulation affected the observed gender differences in decision thresholds. Comparisons of decision thresholds revealed that both male and female participants exhibited lowered decision thresholds in the speed-emphasis condition compared to the accuracy-emphasis condition at each disparity (see SI), suggesting that both genders' decision thresholds were adjusted according to the task instruction. We were specifically interested in examining whether female participants lowered their decision thresholds more than male participants did. Although a comparison of the changes in decision thresholds did not real significant gender differences, it nevertheless suggested a possibility that female participants experienced lower decision thresholds more than male participants in the speed-emphasis condition (e.g., 82% probability at 50°).

Altogether, our findings reveal that the emphasis on speed versus accuracy had a differential impact on the performance of male and female participants, particularly with respect to drift rates. Compared to male participants, female participants exhibited slower drift rates, especially on medium difficulty trials. Decision thresholds were lower in the speed-emphasis condition compared to the accuracy-emphasis condition among participants, though, again, female participants showed somewhat greater effects on medium difficulty trials, suggesting they were more impacted by time pressure.

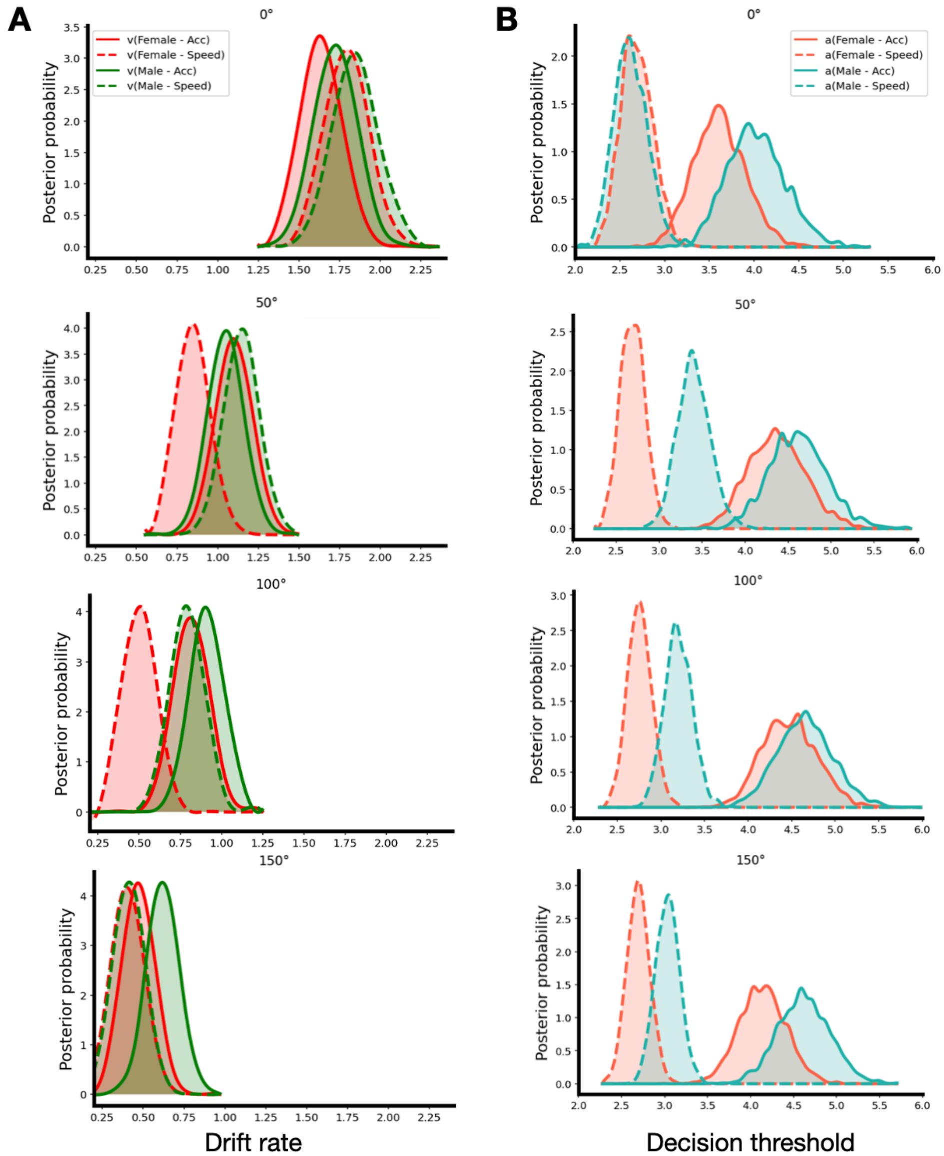



**Figure 4.** Within-gender comparisons of drift rate and decision threshold as a function of angular disparity.

## Discussion

In the present study, we predicted that time pressure would influence processing efficiency and evidence accumulation on mental rotation tasks, with potentially stronger effects in female compared to male participants. Consistent with this hypothesis, we found that, female participants, but not male participants, had slower drift rates in the speed-emphasis condition compared to the accuracy-emphasis condition. These findings suggest that women's processing efficiency was more susceptible to time pressure than men's. With respect to evidence accumulation, we found that when speeded responses were emphasized, both male and female participants lowered their decision thresholds (Ratcliff & McKoon, 2008; Wagenmakers et al., 2008). Modulating the decision strategies based on task demands is a dynamic process, and our results demonstrate that both genders flexibly adapt to task conditions. Less clear known, however, was whether women's decision strategies would be more affected by time pressure than men's. Our results revealed that gender differences in decision thresholds were only evident with time constraints. Given that gender differences were found in the speed-emphasis, but not the accuracy-emphasis, condition, a critical question is why men and women might differ under conditions of time pressure.

**Why might men and women differ in drift rates?**

The findings that women showed slower drift rates than men only in the speed-emphasis condition suggests that time pressure may have impaired women's processing efficiency, particularly when the angular disparities between objects were larger. Previous work on non-mental rotation tasks showed mixed evidence regarding the role of time pressure on processing efficiency (Dambacher & Hübner, 2015). Our work suggests that, on mental rotation tasks, it may depend on trial difficulty and differs between male and female participants. Although previous research across a range of perceptual tasks has established that drift rates are slower when trials ae more difficult (Ratcliff, 2014), extant research had not examined whether men and women differed in drift rates. The findings in the present study showing that gender differences changed as a function of time constraints are consistent with a prior meta-analytic work on mental rotation accuracy (Voyer, 2011).

We speculate that the observed gender differences in the speed-emphasis condition may be related to time pressure-induced affective states. Attentional Control Theory posits that anxiety disrupts information processing (Eysenck et al., 2007). Consistent with this theory, there is evidence for negative associations between anxiety and drift rates (L. Liu et al., 2022; Y. Liu & Lourenco, 2022a). And there is research showing that women experience higher levels of anxiety than men on mental rotation tasks. Thus, it is likely that female participants' decreased drift rates in the speed-emphasis condition was the result of heightened anxiety. However, it remains unclear whether anxiety disrupts processing efficiency through reduced working memory capacity or attention allocation on task stimuli. Our findings of non-decision time (see SI) would seem more consistent the latter possibility. Non-decision time is thought to capture the early stage of sensory filtering (Rae et al., 2014), and our results found that women had longer non-decision time than men in the accuracy-emphasis condition, but the opposite pattern was found in the speed-emphasis condition (see SI Figure 3). These findings suggest that, under time pressure, women may have spent less time in the early perceptual encoding than men. Further evidence is needed to examine this possibility.

**Why might men and women differ in decision thresholds?**

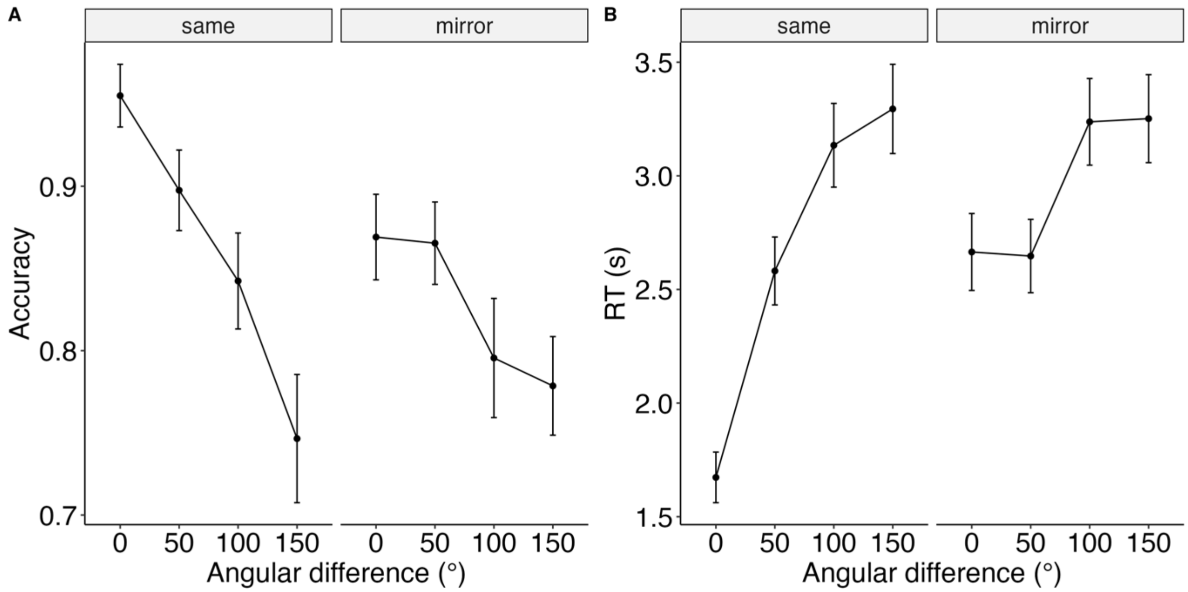
One possibility is that female participants might have altered their decision strategy from a primary concern with accuracy (accuracy-emphasis condition) to a balance between speed and accuracy (speed-emphasis condition). Accordingly, female participants may overcompensate their decision strategy by lowering decision thresholds. However, our results showed that the extent to which female participants lowered their decision thresholds were comparable to men, suggesting that female participants may not have overcompensated on speeded tasks. Another possibility is that women may accumulate, by default, less evidence than men on a mental rotation task. Previous studies have found that men showed larger decision thresholds than women when tasks emphasized both speed and accuracy (Liu & Lourenco, 2022), aligning with our results in the speed-emphasis condition. The findings that such differences diminished when task emphasized accuracy suggest that female participants may have shifted their decision criterion to a more cautious response style.

Past research on the paper-and-pencil version of mental rotation tasks have produced mixed evidence regarding response strategies between men and women. Whereas some studies speculate that women guess more, other studies have argued the reverse. On a standardized mental rotation test (Vandenberg & Kuse, 1978), participants choose among two out of four options to match a rotated target. Two scoring methods vary by whether two or one correct answer(s) receive one point. Meta-analytic reviews on this test found that the scoring method affects the magnitude of the gender difference (Voyer et al., 1995; Voyer et al., 2004). Specifically, gender differences were larger with the scoring method that reduces guessing (i.e., two correct answers for one point) compared to the scoring method that gives credit for guessing (i.e., one correct answer for one point). Although some researchers have argued that women guess more than men (Voyer et al., 1995), others have claimed the opposite (Voyer et al., 2004). Although our results in decision thresholds do not provide direct evidence of guessing behaviors, it may be important to investigate whether gender differences in decision thresholds are related to guessing behaviors.

Taken together, the results from this study suggest that well-known gender differences in mental rotation may be explained by changes in affective states induced by time constraints. Future work should aim to examine the association between affective states and performance changes, while also considering the role of task difficulty.

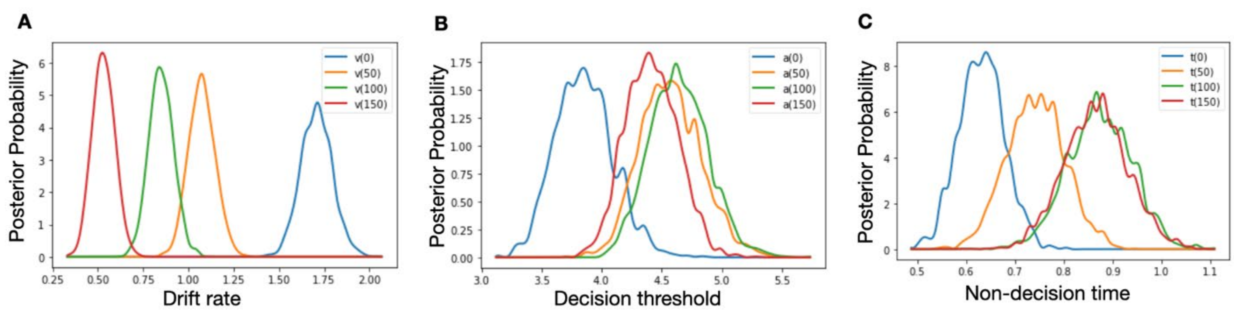
**Supplemental Materials for**
**“Gender differences on mental rotation tasks emphasizing speed over accuracy”**

## Angular disparity effects




**Supplemental Figure 1**. Accuracy and RTs as a function of angular disparity.

The drift rates showed typical linear trends as a function of angular disparity (> 95% posterior probability), consistent with the mental rotation literature.




**Supplemental Figure 2**. Drift rates, decision thresholds, and non-decision time as a function of angular disparity (Model 2).

**Supplemental Table 1.** Model parameters for male and female participants (Model 2)

| Condition | Female | | Male | | *Posterior Probability* |
|---|---|---|---|---|---|
| | *Mean* | *SD* | *Mean* | *SD* | |
| **Accuracy-emphasis** | | | | | |
| Drift rate | | | | | |
| 0° | 1.65 | .11 | 1.73 | .12 | .693 |
| 50° | 1.09 | .10 | 1.04 | .10 | .379 |
| 100° | .81 | .09 | .89 | .09 | .746 |
| 150° | .48 | .08 | .61 | .09 | .846 |
| Decision threshold | | | | | |
| 0° | 3.61 | .29 | 4.01 | .32 | .845 |
| 50° | 4.37 | .33 | 4.61 | .33 | .711 |
| 100° | 4.47 | .31 | 4.65 | .32 | .657 |
| 150° | 4.14 | .27 | 4.60 | .30 | .891 |
| **Speed-emphasis** | | | | | |
| Drift rate | | | | | |
| 0° | 1.80 | .12 | 1.84 | .13 | .611 |
| 50° | .86 | .10 | 1.13 | .10 | **.978*** |
| 100° | .52 | .09 | .78 | .09 | **.982*** |
| 150° | .42 | .09 | .42 | .09 | .526 |
| Decision threshold | | | | | |
| 0° | 2.71 | .18 | 2.64 | .18 | .394 |
| 50° | 2.72 | .14 | 3.42 | .19 | **>.999**** |
| 100° | 2.78 | .14 | 3.22 | .16 | **.982*** |
| 150° | 2.72 | .13 | 3.05 | .14 | **.958*** |

*Note: Posterior probabilities larger than 95% (female < male) was considered as significant differences*

**Supplemental Table 2.** Within-gender comparisons (Model 2)

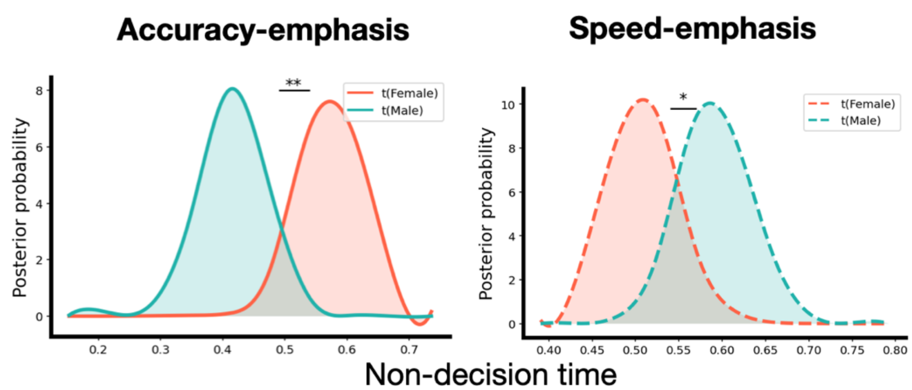
| Gender | Drift rate | Decision threshold |
|---|---|---|
| | *Posterior probability* | *Posterior probability* |
| Female | | |
| All | .778 | **>.999*** ** |
| 0 ° | .196 | **.997*** |
| 50° | **.954*** | **>.999*** ** |
| 100° | **.985*** | **>.999*** ** |
| 150° | .684 | **>.999*** ** |
| Male | | |
| All | .601 | **>.999*** ** |
| 0 ° | .263 | **.999** ** |
| 50° | .263 | **.999** ** |
| 100° | .806 | **>.999*** ** |
| 150° | .931 | **>.999*** ** |

*Note: Within-gender comparisons for drift rates and decision thresholds (Accuracy-emphasis > speed-emphasis)*

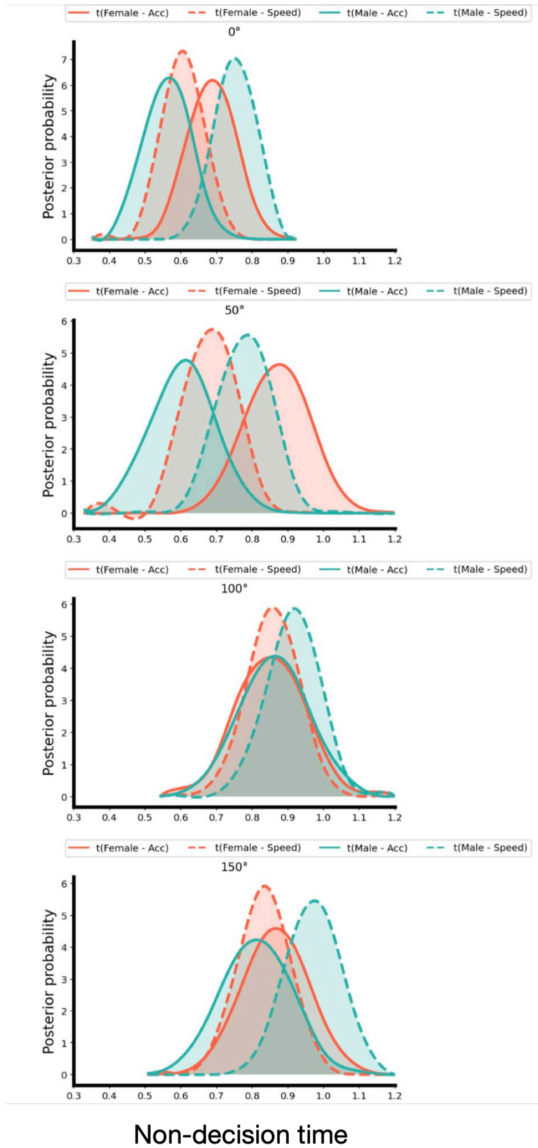
## Non-decision time

The non-decision time ($t$) in the drift diffusion model represents the time taken for processes other than the decision process itself, such as stimulus encoding and motor execution.

Overall, in the accuracy-emphasis condition, female participants showed longer non-decision times than male participants (> 99% posterior probability), and this effect was most pronounced at 50 degrees. In the speed-emphasis condition, male participants showed marginally longer non-decision timse than female participants (94% posterior probability), and this effect varied with disparity.




**Supplemental Figure 3.** Male and female participants' non-decision time across conditions.



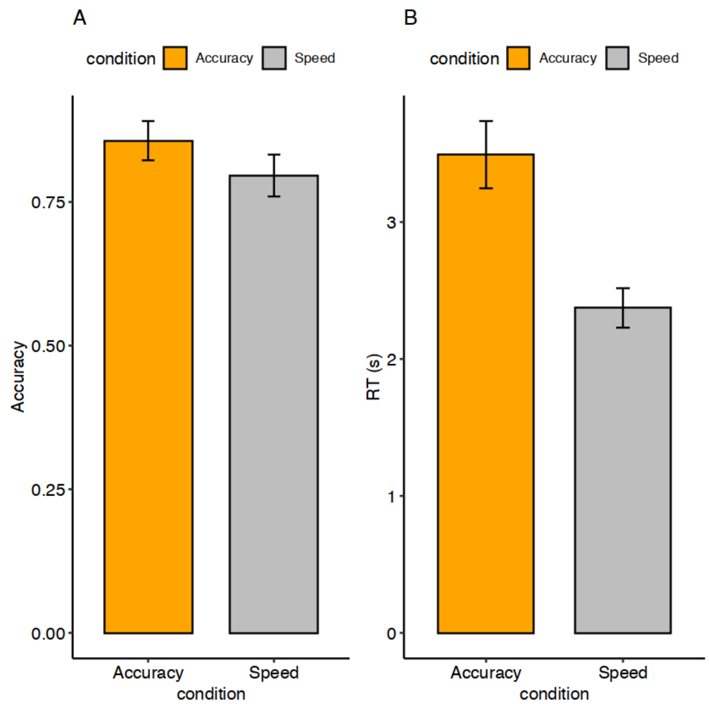

**Supplemental Figure 4.** Within-gender comparisons of non-decision time ($t$) for each disparity. The results revealed that male participants generally had faster non-decision times than female participants, particularly in the speed-emphasis condition.

## Mirror trials

**Accuracy.** A linear mixed model was performed to examine the effects of condition, gender, and their interaction on accuracy of the mirror trials, with participant as a random effect. The Satterthwaite approximation was used to estimate degrees of freedom. The results showed a significant main effect of condition, such that accuracy in the accuracy-emphasis condition was higher than the speed-emphasis condition, $F(1, 164.48) = 5.92$, $M_{\text{difference}} = .06$, $p = .016$. The main effect of gender was not significant, $F(1, 164.48) = 1.90$, $p = .170$, nor was the interaction between condition and gender, $F(1, 164.48) = 0.07$, $p = .798$.

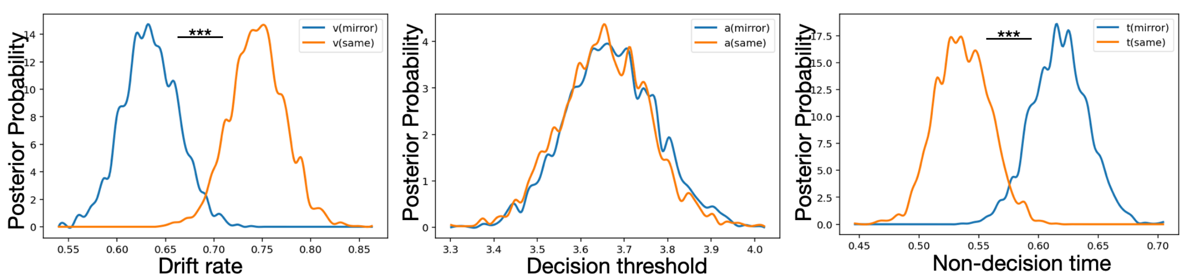
**RTs.** For RTs, the results similarly showed a significant main effect of condition, such that RTs were longer in the accuracy-emphasis than speed-emphasis condition, $F(1, 161.22) = 61.11$, $M_{\text{difference}}$ =

1100 ms, $p < .001$. The main effect of gender was not significant, $F(1, 161.22) = 0.72$, $p = .397$. The interaction between condition and gender was also not significant, $F(1, 161.22) = 0.35$, $p = .553$.




**Supplemental Figure 5.** Accuracy and RTs in both conditions.

## Same versus mirror trials




**Supplemental Figure 6.** Model parameters across same versus mirror trials.

## Model Comparisons

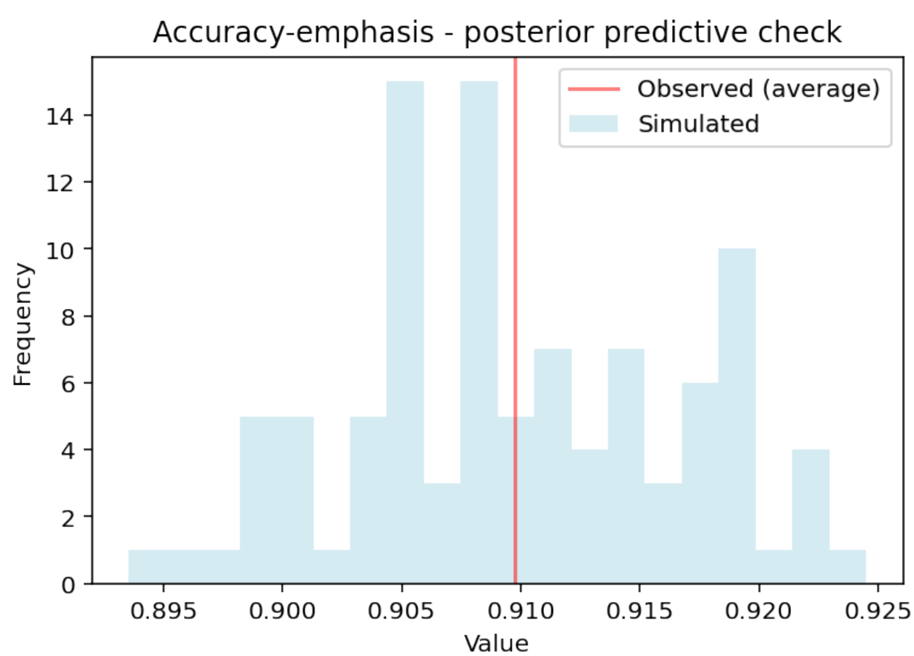
**Supplemental Table 3.** The table presents the Deviance Information Criterion (DIC) for the two models (Gender only and Gender + disparity) in the accuracy-emphasis and speed-emphasis conditions. Lower DIC values indicate a better model fit (Francois & Laval, 2011). For accuracy-and speed-emphasis conditions, the gender + disparity models demonstrated a better fit to the data, as indicated by their lower DIC values.

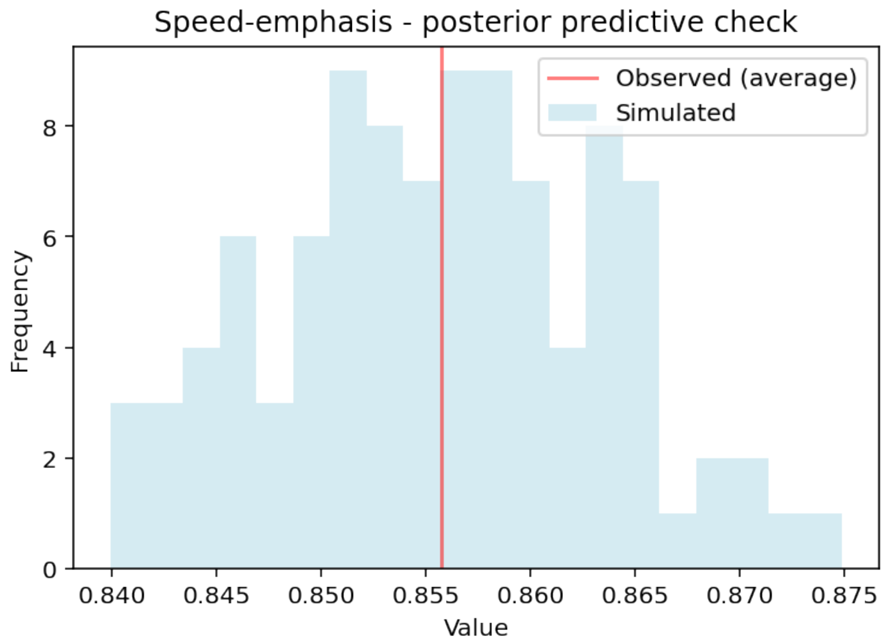
| Condition | Model | DIC |
|---|---|---|
| Accuracy-emphasis | Gender only | 14786.48 |
| Accuracy-emphasis | Gender only | 12965.59 |
| Speed-emphasis | Gender + disparity | 12976.19 |
| Speed-emphasis | Gender + disparity | 11272.72 |

**Model Validation (Posterior Predictive Checks)**

To ensure that the models captured key signatures of behavioral data, posterior predictive checks were performed. Datasets were simulated from the posterior distribution of parameters of the hierarchical models. The simulated data were then compared against the observed data. The observed data closely match the simulated data.

Supplemental Figure 7 represents the results of a posterior predictive check for the models corresponding to accuracy- and speed-emphasis conditions. The histograms show the distribution of the summary statistics (e.g., mean, standard deviation) calculated from the simulated (posterior predictive) data. The red lines indicate the value of the summary statistic calculated from the observed data. The red lines fall within the majority of the histogram, suggesting that the models provide a good fit to the data, as the observed data are consistent with what we would expect t given the model and its estimated parameters.






**Supplemental Figure 7.** Posterior predictive checks.

## Chapter 3 - Affective Factors Affect Visuospatial Decision-making: A Drift Diffusion Modeling Approach (Liu & Lourenco, 2022)

The effects of affective factors such as anxiety, confidence, and motivation on decision making are well documented (Hartley & Phelps, 2012; Lerner et al., 2015). However, little is known about how affective factors influence spatial tasks when effortful decisions are required. One such task is the mental rotation task (MRT), in which participants represent and rotate objects in one's mental space, deciding whether two objects are the same or different (Shepard & Meztler, 1971). This particular type of visuospatial decision making is associated with robust gender differences favoring males (Uttal et al., 2013; Voyer et al., 1995), but it is less clear why they exist and whether affective factors play a role in their instantiation. Research examining the potential role of affective factors in accounting for the gender-performance link provides evidence for mediating roles of spatial anxiety (Alvarez-Vargas et al., 2020; Sokolowski et al., 2019) and confidence (Estes & Felker, 2012) such that when anxiety or confidence is accounted for, gender differences in accuracy diminish. However, an open question remains: what role do affective factors play in influencing mental rotation performance in males and females? Despite the wealth of research on gender differences in spatial cognition, there are few mechanistic explanations for gender differences in terms of the link between affective factors and decision-stage processes.

One potential reason for this void is that it has proven difficult to isolate decision-stage processes from rotational processes on MRTs when using isolated analyses of accuracy and/or reaction time (RT). Previous studies have implemented signal detection theory to estimate the response criterion in the data analyses (Hirnstein et al., 2009). But this response criterion is more sensitive to parametrizing guessing behaviors than to parametrizing decision criterions. Furthermore, speed-accuracy trade-offs in behavioral responses are often inadequately addressed in experimental analyses that focus on accuracy and RT. Little is known about how affective factors influence mental rotation judgments under speed-accuracy trade-offs, as is typical in spatial tasks.

Drift diffusion modeling (DDM), which disentangles the separate stages of decision making, is well suited to dissociate the criteria settings from the quality of evidence accumulation (Ratcliff & Childers, 2015). On MRTs, DDM assumes that, after a stimulus is encoded, information from the stimulus (drift) accumulates with the noisy information (diffusion) until it reaches the decision threshold, at which point, a same/different choice is initiated (see Fig.1A). In this context, RT is the sum of the time needed for the information processing to reach the threshold plus the non-decision time (e.g., motor execution and perceptual encoding time). Thus, rotational processing can be dissociated from decision-stage processing while accounting for speed-accuracy trade-offs. The diffusion model has the following parameters: (1) drift rate ($v$), which represents the efficiency of information processing of mental rotation stimuli; (2) decision threshold boundary ($a$), which represents the amount of evidence needed to judge a same/different choice; and (3) non-decision time ($T$)[7], which represents perceptual encoding and motor execution.

Here, through DDM, we investigate the link between affective factors and mental rotation decision-making in males and females. To our knowledge, no study has incorporated DDM in an investigation of affective factors in mental rotation in order to shed light on the gender difference in

[7] Nondecision time (*T)* and a priori bias (*z)* are not considered further in the present paper. *T* is composed of encoding + motor execution. Although some researchers have suggested that males and females differ in their encoding of the stimuli, encoding and motor execution are not dissociable in this analysis. Thus, we do not report analyses of *T*. *z* is assumed to be 0.5 (i.e., equal bias for either choice) for both genders; thus, *z* is not reported.

performance. A major strength of the current approach is that we are able to compare gender differences in both the rotational and decision-stage processes.

**Anxiety.** State anxiety, which is a transitory fear or apprehension towards a stimulus (Spielberger, 1983), can either enhance decisions by heightening perception of the stimulus or impair decisions by disengaging attention from the stimulus (Hartley & Phelps, 2012). Here, we hypothesized that anxiety would be associated with decreased information processing efficiency (i.e., drift rate). This hypothesis follows from attentional control theory (Coombes et al., 2009; Eysenck et al., 2007; Shackman et al., 2006), which suggests that higher anxiety drains working memory resources needed for tasks such as mental rotation. Moreover, such rumination may be particularly damaging to an analytical strategy (i.e., comparing parts or features of objects), which may be overrepresented in females (Geiser et al., 2006). We also hypothesized that higher state anxiety might be associated with a lower decision threshold because anxious individuals are more likely to engage in an avoidance strategy which could involve disengagement from evidence accumulation. Related research on math anxiety suggests such a possibility insofar as math anxious individuals engage in avoidance behaviors by decreasing effort on math problems (Choe et al., 2019).

**Confidence.** Confidence is defined as the degree to which one believes that one's judgment is correct. Studies have found that confidence is positively correlated with mental rotation accuracy in both male and female participants, but males report relatively higher confidence (Cooke-Simpson & Voyer, 2007; Estes & Felker, 2012). There is also evidence that when participants are allowed to update their initial answer on a mental rotation task, females (who report relatively lower confidence) revise their answers more than males (Cross et al., 2017). Given these findings, we hypothesized that confidence would be positively associated with drift rate by enhancing processing efficiency and negatively correlated with decision threshold by decreasing the amount of evidence accumulation.

**Motivation.** Motivation is defined as the willingness to achieve a task goal. Whereas anxiety captures fear and nervousness in spatial experiences, motivation captures how one approaches spatially-related activities and the amount of effort one exerts on a task. Previous research has shown that mental rotation performance improves when conditions elevate motivation, such as self-affirmation (Martens et al., 2006), compensating stereotypes (Wraga et al., 2006), and believing that effort and practice matter, particularly in female participants (Moè & Pazzaglia, 2010). However, it remains unclear how motivation affects drift rate and/or decision threshold across genders. We hypothesized that motivation might be positively correlated with drift rate by enhancing information processing efficiency and positively correlated with decision threshold by increasing the amount of evidence accumulation.

Each of the aforementioned affective factors may operate independently on performance or by way of interactions with each other. To this end, we examined the mediating roles of affective factors in accounting for gender-performance links. We were particularly interested in the gender-specific effects of affective factors on decision-making because, as previously noted, females tend to report higher levels of spatial anxiety and lower levels of confidence compared to males.

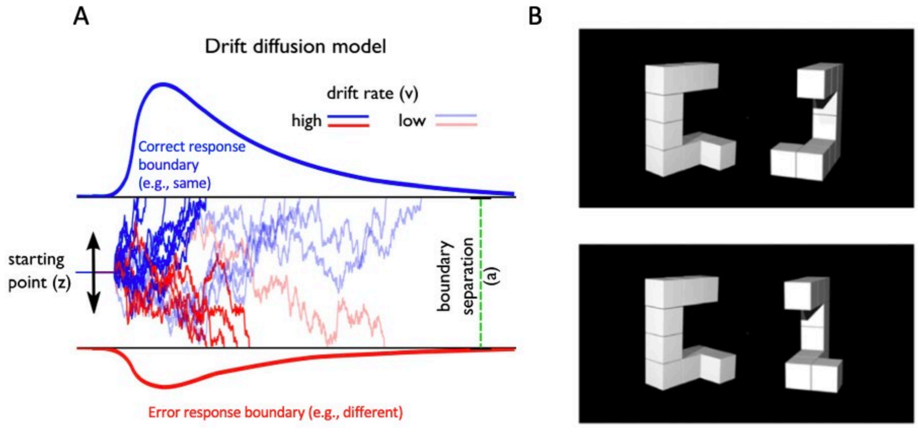



Fig.1. (A) Schematic illustration of the drift diffusion model. Information accumulates until a boundary is reached. Adapted from HDDM (Wiecki et al., 2013) in the context of a same trial. (B) Examples of same (top) and different (bottom) trials on the MRT (Ganis & Kievit, 2015).

## Method

### Participants

106 adults were recruited through the *Prolific* online testing platform (50% males; age range:18 – 40 years). All participants were right-handed and reported normal or corrected-to-normal vision. All participants reported that their gender identity matched their birth sex. Written informed consent was provided prior to participation. A sample size of 100 was determined by a priori power analysis. Experimental procedures were approved by the Emory University Institutional Review Board (IRB).

### Procedure

**Mental Rotation Task (MRT).** Participants completed a chronometric 2AFC MRT (Fig. 1B), in which participants judged whether pairs of objects were identical or different. Objects were selected from a stimulus library with enhanced perspective, depth, and shading cues compared to the original stimuli of Shepard and Metzler (1971) (Ganis & Kievit, 2015). Object pairs are considered identical if one object can be rotated into congruence with the other ('same' trials) and different if they cannot be rotated into congruence ('different/mirror' trials). Across a total of 96 trials, object pairs differed by one of four orientations: 0°, 50°, 100°, and 150° (counterbalanced order), with an equal number of same and different trials.

Participants were instructed to "respond as quickly and as accurately as possible" within 7500 ms, and they received a prompt to respond without the stimulus after the elapsed time. Trials were separated by an interval of 200 ms.

**State Affective Factors.** In 24 randomly-selected trials (balanced across angular disparity and blocks), participants rated their levels of anxiety, confidence, and motivation for the preceding trial using a 7-point Likert scale (i.e., "How anxious/confident/motivated were you on the previous trial?"; 1 = *not at all,* 7 = *extremely*). Presentation order for each rating type (anxiety, confidence, or motivation) was counterbalanced across trials.

**Trait Anxiety.** At the end of the MRT, general (trait) anxiety was assessed by the trait subscale (STAI-T) of the State-Trait Anxiety Inventory (Spielberger et al., 1983). Participants rated their level of anxiety on 20 statements (e.g., "I feel like a failure"; 5-point scale). Trait anxiety was used as a contrast to state affective factors in order to test for the specificity of effects.

Hierarchical Drift Diffusion Modeling (HDDM)

Task performance was modeled by fitting HDDM (Wiecki et al., 2013) to participant accuracy and RT data. This approach accounts for individual differences in parameter estimates. All models were fit to individual participants' data using hierarchical Bayesian analyses.

**Pre-processing of RT data.** Of the 106 participants, six were excluded due to technical problems or a failure to pass attention checks. The final sample consisted of 100 participants (50% males). Data were trimmed by removing RTs faster than 300 ms and slower than 7500 ms (1.2% of total trials); RTs were also trimmed per participant (2.5 SD). Both correct and error trials were included in the analyses. Trial-by-trial RT and accuracy data for each participant were inputted into HDDM.

Model specifications. Parameter estimates consisted of drift rate ($v$) and decision threshold ($a$). Group mean posteriors of the hierarchical model were used to perform statistical analyses. All models excluded 5% of outlier trials and used weakly informative priors by default (Wiecki et al., 2013).

Models were fitted to same and different trials separately because these two types of trials may be processed differently and diverge early in processing (Toth & Campbell, 2019). For simplicity, only the same trials are analyzed in the current paper. Analyses of different trials can be found in supplemental material (OSF link).

**Model fits.** HDDM was checked for model convergence by inspecting traces of model parameters and the Gelman-Rubin convergence diagnostic statistics (Gelman & Rubin, 1992). Model parameters were analyzed using Bayesian hypothesis testing (95% Credible Intervals).

## Results

In preliminary analyses, we confirmed that both accuracy and RTs varied as a function of the angular disparity between objects. As angular disparity increased, participants' accuracy decreased ($\beta$ = -.18, $p$ < .001) and RTs increased ($\beta$ = .81, $p$ < .001), consistent with the angular disparity effect.

### Gender Differences in Model Parameters and Affective Ratings

**Model Parameters.** Analyses of drift rate and decision threshold also revealed effects of angular disparity. DDM fits for drift rate decreased monotonically with angular disparity (Fig. 2A; posterior probability > 95%), whereas decision threshold, increased with angular disparity (Fig. 2B, posterior probability > 95%), as expected if trials with larger angular differences between objects are relatively more difficult. These results demonstrate that model fits captured the patterns observed in behavior (with accuracy and RT), providing support for DDM as a valid index of performance.

Subsequent analyses tested for effects of participant gender. DDM fits for drift rate revealed lower drift rates for females compared to males (Fig. 2C, 97.1% posterior probability), suggesting slower information uptake in female participants compared to male participants. In the case of decision threshold, the gender difference approached significance (Fig. 2D; 92.7% posterior probability), with female participants displaying a relatively smaller decision threshold compared to male participants, which may indicate an avoidance strategy in decision making as reflected by less evidence accumulation.

**Affective Ratings.** Mean ratings were obtained across the rating trials. A MANOVA, with gender as a fixed factor, was conducted; the dependent variables were state affective ratings (anxiety, confidence, motivation), and trait anxiety (Table 1). There were significant gender differences in state anxiety and confidence, with females reporting higher anxiety and lower confidence than males. No other significant gender differences were found, though state motivation approached significance (such that females were relatively more motivated on the task).

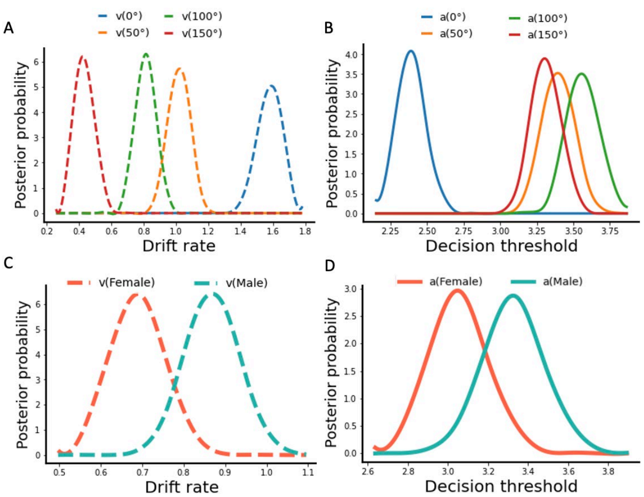



Fig. 2: DDM fits for angular disparity (A & B) and gender (C & D).

Table: 1: Means, *SD*s, *F* Values, *p* Values, and Effect Sizes for Comparisons of Gender Differences

| Predictor | Female | | Male | | | | |
|---|---|---|---|---|---|---|---|
| | Mean | *SD* | Mean | *SD* | *F* | *p* | $\eta_p^2$ |
| State anxiety | 2.98 | 1.53 | 2.41 | 1.15 | 4.32 | .040* | .04 |
| State confidence | 4.65 | 1.25 | 5.27 | 1.17 | 6.48 | .012* | .06 |
| State motivation | 5.63 | 1.27 | 5.14 | 1.54 | 3.04 | .085 | .03 |
| Trait anxiety | 50.10 | 11.92 | 46.76 | 10.02 | 2.30 | .132 | .02 |

*Note:* * $p < .05$

## Relations Between Affective Ratings and Model Parameters

We next performed separate regression analyses to test for relations between each of the affective ratings and model parameters, controlling for trait anxiety. Affective ratings and trait anxiety were standardized.

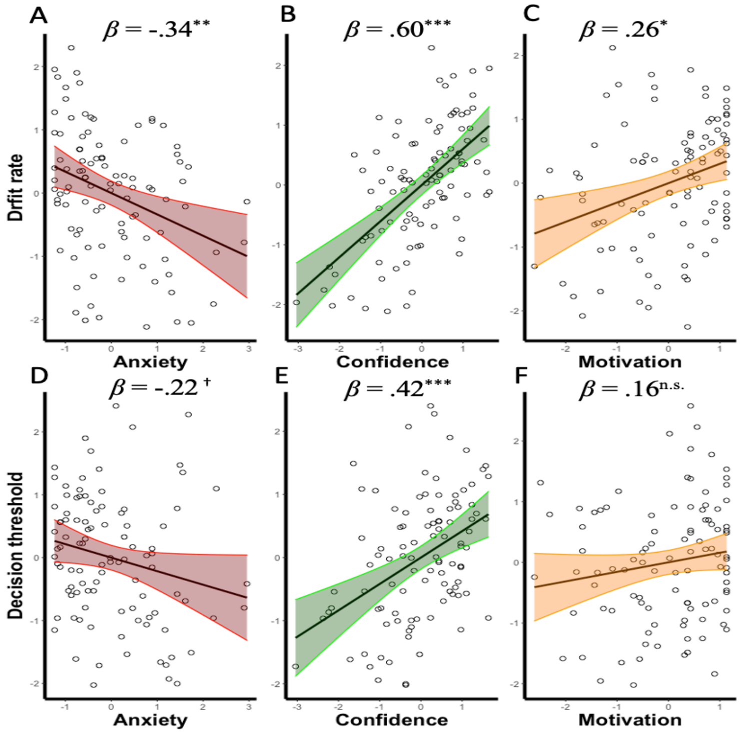



Fig. 3: Partial regression plots of the relations between each of the affective ratings and each model parameter (drift rate and decision threshold), controlling for trait anxiety. Betas are standardized coefficients. $^{\dagger}p = .05 - .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

**Anxiety**[8]. Higher state anxiety was associated with lower drift rates (Fig. 3A; $\beta = -.34$, $p = .002$, 95% CI [-.55, -.12]), and there was a marginal association with decision thresholds (Fig. 3D; $\beta = -.22$, $p = .055$, 95% CI [-.44, .01]). These findings suggest that state anxiety may disrupt processing efficiency. Its effect on evidence accumulation, however, is less clear. Although not statistically significant, the negative coefficient indicates that participants may have decreased evidence accumulation as anxiety increased.

**Confidence.** Higher confidence was associated with both faster drift rates (Fig. 3B; $\beta = .60$, $p < .001$, 95% CI [.44, .77]) and higher decision thresholds (Fig. 3E; $\beta = .42$, $p < .001$, 95% CI [.23, .61]). These findings suggest that confidence affects both processing efficiency and evidence accumulation, such that, when confidence is higher, processing efficiency is better and participants engage in more evidence accumulation.

**Motivation.** Higher motivation was associated with faster drift rates (Fig. 3C; $\beta = .60$, $p = .011$, 95% CI [.06, .45]), but there was no association with decision thresholds (Fig. 3F; $\beta = .16$, $p = .120$, 95% CI [-.04, .36]), suggesting that motivation enhances processing efficiency but may not affect evidence accumulation.

**Do Affective Factors Account for the Gender Differences in Model Parameters?**

[8] Analyses of the relation between trait spatial anxiety (SAQ; Lyons et al., 2018) and model parameters found similar results.

Given the aforementioned effects of gender and affective factors on model parameters, we next tested for mediation by affective factors (anxiety, confidence, and motivation) between gender and model parameters in separate analyses. Gender was dummy coded (female = 0, male = 1) so that positive coefficients indicated higher scores for male participants. All variables were standardized. Effects were assessed by bias-corrected bootstrapped 95% CIs from 2000 resamples. Gender positively predicted anxiety ($\beta$ = .47, 95% CI [.08, .85]), but negatively predicted confidence ($\beta$ = .50, 95% CI [.11, .88]). Gender was not significantly correlated with motivation ($\beta$ = -.35, 95% CI [-.74, .05]). Tests of mediation for anxiety, confidence, and motivation are presented next.

**Drift Rate.** As shown in Figure 4A, analyses revealed that with the inclusion of confidence, the direct effect between gender and drift rate became non-significant, suggesting that confidence mediated the path between gender and drift rate. By contrast, there was no evidence of mediation by anxiety or motivation. Importantly, we included gender as a mediator to test for model misspecification; gender was not significant. Altogether, these results provide evidence for a unique effect of confidence in accounting for the gender difference in processing efficiency on the MRT.

We next tested for whether anxiety or motivation moderated the mediation effect of confidence. We specified that anxiety or motivation moderated both the indirect and direct paths in the mediation models. Results revealed that motivation, but not anxiety, moderated the path from gender to drift rate (Fig. 4C). Simple mediated effects showed that confidence partially mediated the relation between gender and drift rate in participants with low motivation, as path *c'* was lower than path *c*, but still significant. By contrast, participants with high motivation did not show gender differences in drift rates (non-significant *c* and *c'* paths). These results suggest that the mediating role of confidence in the gender-drift rate link may be specific to participants who are low in motivation.

**Decision Threshold.** Although gender only marginally predicted decision threshold (92.7% posterior probability), we nevertheless tested for the mediating roles of all affective factors, given extant findings and a priori predictions. As Figure 4B illustrates, analyses revealed that with the inclusion of confidence, the direct effect between gender and decision threshold was non-significant, suggesting a mediating role of confidence along this path. By contrast, there was, again, no evidence of mediation by state anxiety or state motivation. Importantly, we also included gender as a mediator to test for model misspecification; gender was not significant. These findings suggest a unique role for confidence among the affective factors in accounting for the gender difference in evidence accumulation on the MRT.

We then tested for whether anxiety or motivation moderated the mediating effect of gender to decision threshold through confidence. Results showed that motivation, but not anxiety, moderated the path from gender to decision threshold (Fig. 4D). Simple mediated analyses showed that confidence partially mediated the relation between gender and decision threshold in participants with low motivation, as path *c'* was lower than path *c*, but still significant. By contrast, participants with high motivation did not show gender differences in decision thresholds (non-significant *c* and *c'* paths). These results suggest that the mediating role of confidence in the gender-decision thresholds link may be specific to participants with low motivation.

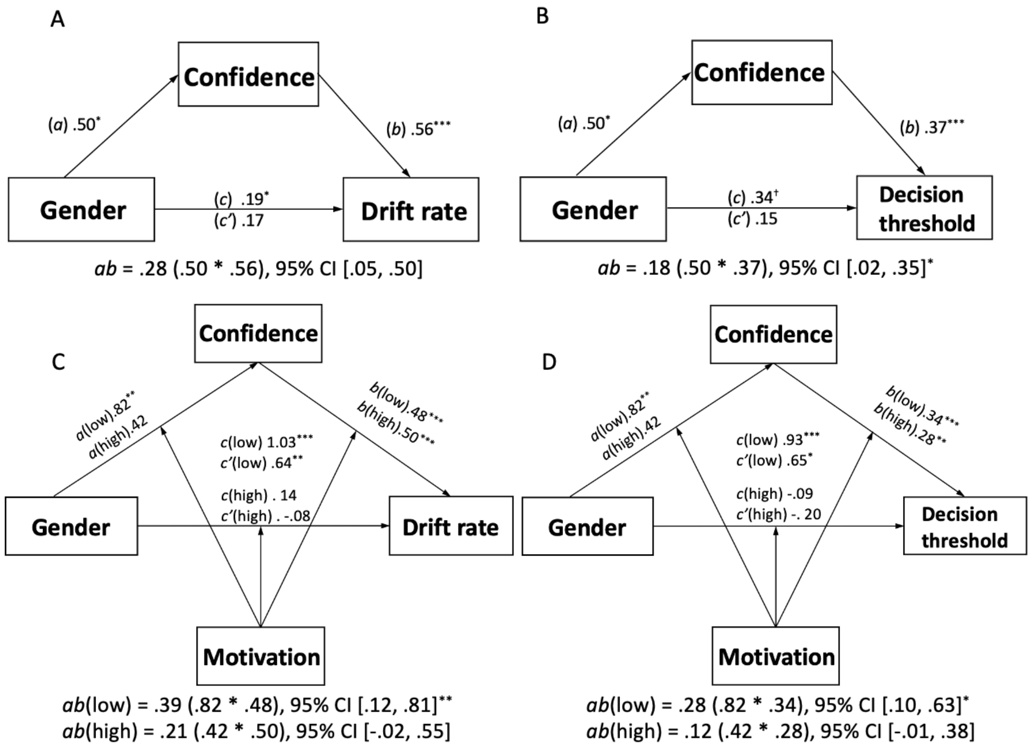



Fig. 4: Path diagrams showing standardized coefficients for mediation models of drift rate (A) and decision threshold (B), as well as conditional indirect effects of gender and drift rate (C) and gender and decision threshold (D) via confidence, at low (-1 SD) and high (+1 SD) motivation. The *c* paths represent the total effects. The *c'* paths represent the direct effects. The *ab* paths represent the indirect effects. Only significant (or marginal) effects are noted: $^{\dagger}p = .05 - .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

## Discussion

The present study provides a novel exploration of performance-related factors on a visuospatial task, for which gender differences have been robustly reported. Using DDM, we shed new light on the potential roles of affective factors in the gender-performance link on a MRT.

We found that anxiety was negatively associated with drift rate, whereas confidence and motivation were positively associated with drift rate. In other words, although higher anxiety reduces processing efficiency, higher confidence and higher motivation enhance it. We also found that only confidence predicted decision threshold, such that participants accumulated more evidence when more confident. Taken together, these findings highlight important relations between affective factors and decision making such that anxiety, confidence, and motivation may all affect processing efficiency. Confidence, however, was the only affective factor to mediate the links between gender and both processing efficiency and evidence accumulation.

**Anxiety.** Consistent with our hypothesis, our results establish a robust link between anxiety and processing efficiency, in line with attentional control theory (Eysenck et al., 2007; Ramirez et al., 2012). We also found some preliminary evidence supporting the role of anxiety in decision threshold, which may suggest that high levels of anxiety induce avoidance, with less evidence accumulation during the task. This appears consistent with studies showing that participants react faster after a fearful stimulus than after a neutral stimulus on MRTs (Borst et al., 2012). However, it is an open question whether anxiety may interact with other affective factors to increase the decision threshold rather than decrease it.

**Confidence.** Our results showed that confidence is positively associated with processing efficiency and evidence accumulation. Based on this, confidence may offset anxiety to increase processing efficiency and evidence accumulation. Previous work in line with such a possibility found reductions of drift rate after errors (Notebaert et al., 2009; Purcell and Kiani, 2016), such that error processing may have diverted attention from the task at hand (Desender et al., 2019). Relatedly, participants may engage less with the task after perceived errors, eliciting avoidance, perhaps similar to the effects of anxiety on decision thresholds. This suggests a potential role for metacognitive monitoring of the difficulty and accuracy of responses.

**Motivation**. Our results highlight that motivation may enhance both processing efficiency and evidence accumulation. In post hoc analyses, we found that whereas motivation is positively associated with drift rates and decision thresholds in female participants, such relationships were not observed in male participants. Previous work has suggested that teaching motivation is particularly effective for females in MRTs (Moè, 2016), and our results are in line with such a possibility.

**Confidence and Motivation.** A novel finding of the current work is that confidence mediates the gender differences in drift rate and decision threshold in individuals with low motivation. It is possible that confidence, resulting from perceived correctness, may boost approach behaviors in females with low motivation who have adopted an avoidance motivation strategy, resulting in increases in processing efficiency and evidence accumulation comparable to that of males. However, females and males with high motivation may have had an approach motivation strategy that works optimally on the task regardless of how they perceived the accuracy of their answers. This possibility highlights the importance of motivation in affecting gender differences on MRTs. However, given that the mediation (vis-à-vis confidence) was only partial, future work will be needed to decipher the role of other potential mediators.

In sum, our findings motivate theoretical questions about how affective factors influence decision making on MRTs. We suspect that our results will have implications for reducing gender differences in spatial tasks by targeting affective interventions, such as boosting confidence and motivation.

**Supplemental Materials for**
**"Affective Factors Affect Visuospatial Decision-making: A Drift Diffusion Modeling Approach"**

**Supplemental Information:** https://osf.io/s7hkc/

# Chapter 4 - The effects of motivational and affective states on spatial information processing and decision strategies

Avoiding failure and punishments (*avoidance motivation*) versus striving for success and rewards (*approach motivation*) have been associated with differential decision-making behaviors (Elliot, 2008). Whereas avoidance motivation is associated with vigilance and cautious responding so as to avoid negative outcomes, approach motivation is associated with risk-taking and flexible responding for positive outcomes (Roskes et al., 2014). Moreover, these two types of motivation are tied to distinct patterns of information processing. Avoidance motivation, with its emphasis on vigilance and focus, is associated with structured, controlled information processing, particularly when attention to details is needed (Koch et al., 2008; Miron-Spektor et al., 2011). By contrast, approach motivation is associated with flexible and holistic information processing (Friedman & Forster, 2002).

Despite the well-known distinction between approach and avoidance motivation, the nature of motivational states on cognitive performance, generally, and spatial performance, specifically, remains relatively unclear (Lourenco & Liu, 2023). Previous findings have shown that approach motivation is associated with better performance on spatial learning (Murty et al., 2011). Murty and colleagues, for example, found that spatial learning, incentivized by rewards rather than electric shock, was associated with better task performance on a navigation task. In another study testing mental rotation performance, approach behaviors induced by arm extension, which presumably elicited approach motivation, improved task performance compared to avoidance behaviors induced by arm flexion (Jansen et al., 2017). In addition, motivational instructions to boost self-confidence and self-affirmation, combined with instructions to adopt a holistic processing strategy, were found to enhance mental rotation performance more than either strategy training or motivation-boosting instructions alone (Moè, 2016).

How does approach/avoidance motivation influence task performance? One possibility is approach/avoidance motivation influences how information is processed. In this vein, approach motivation is associated with more global focus, or broader attention, which promotes attentional flexibility and holistic processing (Friedman & Forster, 2002). For example, implicit approach cues (e.g., arm enactment) facilitated flexible and creative thinking, but avoidance cues impaired creative thinking (Friedman & Förster, 2001). On a global-local task, in which participants switched between attention allocation to global versus local stimuli (e.g., composite letters), it was found that approach motivation led to faster attentional flexibility, whereas avoidance motivation led to mixed results that depended on the amount of global/local cues (Calcott & Berkman, 2015). These findings suggest that approach/avoidance motivation influences task performance via attentional flexibility. Furthermore, a motivation to obtain rewards (approach) that are contingent on performance appear to speed up participants' response times (Chiew & Braver, 2014; Fröber & Dreisbach, 2014), though it is unknown whether this is due to enhanced information processing or decision-making.

Relatedly, approach/avoidance motivation is associated with goal pursuit and the facilitation of task decisions. For example, approach motivation has been found to associate with the narrowing of goal pursuit, promoting decisions related to task goals (Gable & Dreisbach, 2021; Threadgill & Gable, 2016). Goal pursuit under approach motivation may be associated with information seeking and gathering to increase the likelihood of achieving goals. Thus, such approach-oriented motivational states may affect decision-making by increasing response caution or effort. Alternatively, avoidance motivation is associated with threat avoidance, which may elicit greater decision caution in order to avoid negative outcomes (Yee et al., 2022). Findings from studies on math anxiety suggest that the avoidance of threating stimuli (e.g., math problems, in this case) is associated with escape behaviors by responding more quickly (Choe et al., 2019).

A rich body of literature from the affective sciences suggests that affective states modulate approach/avoidance motivation (Gable & Dreisbach, 2021), which, in turn, influence information processing and decision making (Roberts & Hutcherson, 2019). Positive affect, which often co-occurs with approach motivation, for example, is associated with cognitive flexibility, creative decision-making (Fredrickson, 2013), and a preference for global (compared to local) visual processing (Gasper & Clore, 2002). However, negative affect, which may be accompanied by avoidance motivation, is associated with slower information processing, biased decisions, and greater response caution (Roberts & Hutcherson, 2019). Although affect is closely associated with motivational state, they are nevertheless dissociable (see reviews, see, Gable & Dreisbach, 2021; Berridge & Robinson, 2003). For example, negative affect, such as anger, can produce approach-oriented motivational states (Carver & Harmon-Jones, 2009). Additionally, the intensity of affect moderates approach/avoidance motivation. For example, it has been shown that high or low affect intensity has differential effects on approach motivation, resulting in changes in cognitive performance (Threadgill & Gable, 2016). Thus, both the dimension of valence (positive/negative) and intensity (low/high) of affect may interact with motivational states.

Affective states are well known to permeate information processing and decision-making. During cognitive tasks, stimulus processing and decision-making are subject to emotion and motivational states experienced at the time (Lerner et al., 2015). However, it remains elusive how such mechanisms function on spatial tasks. Considering the dissociation between affect and motivational states, we were particularly interested in examining how information processing and decision making are affected by motivational states (approach/avoidance) while examining the associations between affect (e.g., state anxiety, confidence, and motivation), information processing, and decision making.

**Present Study**

Across two experiments, we examine the influences of approach/avoidance motivation and affective states on a mental rotation task that favors holistic processing. On mental rotation tasks, participants are typically required to decide whether two objects can be rotated into congruence (see Figure 1). At the start of encoding, participants are equally likely to make a 'same' (congruent) or 'mirror' (incongruent) judgment. When participants begin to mentally rotate objects, the information from the stimuli is nosily accumulated until a same/mirror decision is made. This process of noisy accumulation of information may be particularly susceptible to affective and motivational states. Using drift diffusion modeling (DDM), we are able to dissociate information processing and decision-making (Forstmann et al., 2016; Ratcliff & McKoon, 2008; Ratcliff & Rouder, 1998). In this context, the speed of information uptake (drift rate) can be separately modeled from the amount of evidence accumulation (decision threshold). The faster the drift rates, the faster the information processing; the larger the decision thresholds, the larger the amount of evidence accumulation. This model is particularly suitable for the present research, as approach/avoidance motivation may influence drift rates, decision thresholds, or both.

We manipulated approach or avoidance motivation on the mental rotation task by presenting task goals as either monetary gains (approach) or losses (avoidance) (Dix & Li, 2020; Spliethoff et al., 2022) . We assessed affective states, including state anxiety, confidence, and motivation, throughout the task in each condition. To assess the subjective evaluation of the task goals and incentive value of task goal pursuit in approach versus avoidance condition, we also included a questionnaire evaluating participants' motivational patterns at the end of the testing session.

We made three sets of predictions. The first set was concerned with the effects of approach versus avoidance motivation on drift rates and decision thresholds. We hypothesized that approach motivation, compared to avoidance motivation, would be associated with faster information processing (i.e., faster drift rate), particularly because a mental rotation task should elicit holistic processing. We also hypothesized that if approach motivation is associated with evidence accumulation, then it should lead to a decision strategy that favors more evidence accumulation (i.e., larger decision threshold). By contrast, if avoidance motivation is associated with threat avoidance and caution, then avoidance motivation should lead to a decision strategy that favors less evidence accumulation (i.e., smaller decision threshold).

The second set of predictions was broadly concerned with affect and its potential relations to information processing and evidence accumulation. Generally, we hypothesized that greater positive affect (i.e., confidence) should be associated with faster drift rates because positive affect is associated with greater cognitive and attentional flexibility (Fredrickson, 2013). Based on our prior research (Liu & Lourenco, 2022), we also hypothesized that greater positive affect should be associated with greater evidence accumulation.

The third set of predictions concerned gender differences in information processing and evidence accumulation, as well as the potential interactions between gender, motivational state, and affect. Given our prior research showing that affective states (e.g., state motivation) moderated gender differences in drift rates and decision thresholds (Liu & Lourenco, 2022), we hypothesized that men and women would differ in their motivational and affective states, and we examined whether gender might modulate the relations between affective states, drift rates and/or decision thresholds.

## Experiment 1

In Experiment 1, we manipulated approach and avoidance conditions in a between-subject design. As a first step, we were interested in examining how drift rates and decision thresholds would vary as a function of task condition (approach/avoidance) and gender.

## Method

### Participants

A total of 116 adults were recruited online through *Prolific*: participants were randomly assigned to either the approach motivation condition or the avoidance motivation condition (50% males; age range: 18 – 40 years). All participants were right-handed and reported normal or corrected-to-normal vision. All participants reported that their gender identity matched their birth sex. Written informed consent was provided prior to participation. A minimum sample size of 100 was determined by an a priori power analysis using effect sizes from pilot data ($\eta^2$= .08; power = 0.8; alpha = 0.05; BUCSS R package). Thus, the current size exceeds the minimal sample size. Experimental procedures were approved by the Emory University Institutional Review Board (IRB).

## Procedure

**Mental Rotation Task (MRT).** Participants completed a chronometric 2AFC MRT, in which participants judged whether pairs of objects were identical or different (see Figure 1A). Objects were selected from a stimulus library with enhanced perspective, depth, and shading cues compared to the original stimuli of Shepard and Metzler (1971) (Ganis & Kievit, 2015). In this task, object pairs are considered identical if one object can be rotated into congruence with the other ('same' trials) and different if they cannot be rotated into congruence ('mirror' trials). Across a total of 40 trials, object pairs differed in 150°, with an equal number of same and mirror trials.

Participants were instructed to "respond as quickly and as accurately as possible" within 7500 ms, and they received a prompt to respond without the stimulus after the elapsed time. Trials were separated by an interval of 200 ms. Participants completed practice trials with corrective feedback. All participants received a base payment of $1.28 and the study was advertised to last around 8 minutes ($9.60/hour). Additional (incentive) payment depended on the condition.

**Conditions.** In the *approach* condition, participants were instructed that their goal was to earn as much bonus payment as possible by getting as many correct answers as possible. Participants earned 6 cents for each correct trial that was within the time limit, up to a maximum payment of $2.40. In the *avoidance* condition, participants were instructed that their goal was to avoid a loss of the bonus payment. Participants lost 6 cents for each incorrect trial, or a trial not within the time limit, up to a total loss of $2.40. To ensure that participants understood the task instructions, they were given a comprehension check, which consisted of three true/false questions about the task goals.

**State Affective Factors.** In 10 randomly selected trials (balanced across same/mirror trials), participants rated their levels of anxiety, confidence, and motivation for the preceding trial using a 7-point Likert scale (i.e., "How anxious/confident/motivated were you on the previous trial?"; 1 = *not at all,* 7 = *extremely*; as in Liu & Lourenco, 2022). Presentation order for each rating type (anxiety, confidence, or motivation) was counterbalanced across trials.

**Approach/Avoidance System Questionnaire.** At the end of the experiment, participants completed the Approach-Avoidance System Questionnaire (AASQ; Teboul et al., 2019). This questionnaire measures three factors: (1) competence expectancies regarding a goal; (2) benefit to the self when a goal is reached; and (3) threat to the self when a goal is not reached.

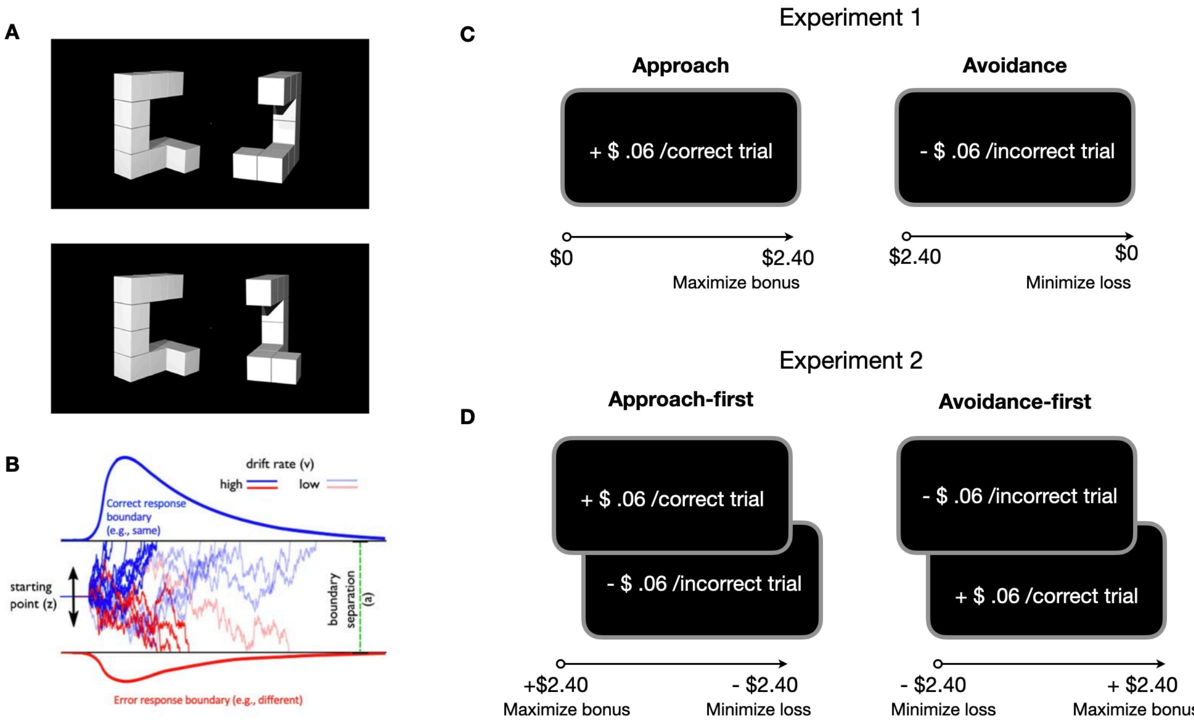



**Figure 1.** A. Examples of mental rotation trials ('same': top; 'mirror': bottom). B. A schematic illustration of drift diffusion modeling. C. The study procedure in Experiment 1. D. The study procedure in Experiment 2.

**Hierarchical Drift Diffusion Modeling (HDDM)**

Task performance was modeled by fitting HDDM (Wiecki et al., 2013) to participant accuracy and RT data. This approach accounts for individual differences in parameter estimates. All models were fitted to individual participants' data using hierarchical Bayesian analyses.

**Pre-processing of RT data.** Of the 116 participants, three were excluded due to technical problems or a failure to pass comprehension checks (i.e., they incorrectly answered 2 out of 3 questions on task instructions). The final sample consisted of 113 participants (57 in the approach condition and 56 in the avoidance condition). Data were trimmed by removing RTs faster than 300 ms and slower than 7500 ms (1.5% of total trials). Both correct and error trials were included in the analyses. Trial-by-trial RT and accuracy data for each participant were inputted into HDDM.

**Model specifications.** Parameter estimates consisted of drift rate ($v$) and decision threshold ($a$). Group mean posteriors of the hierarchical model were used to perform statistical analyses. All models excluded 5% of outlier trials and used weakly informative priors by default (Wiecki et al., 2013).

Models were fitted separately to same and mirror trials because these two types of trials may be processed differently and diverge early in processing (Toth & Campbell, 2019). Preliminary analyses comparing the accuracy of same and mirror trials found a significant effect of trial type on accuracy. Specifically, participants were more accurate on same trials compared to mirror trials ($M_{\text{difference}}$ = .06, $t$[224] = 2.48, $p$ = .015), as has been found in other research (Paschke et al., 2012). Given these differences, the subsequent models were fitted separately for same and mirror trials.

**Model fits.** HDDM was checked for model convergence by inspecting traces of model parameters and the Gelman-Rubin convergence diagnostic statistics (R-hat; Gelman & Rubin, 1992). All models showed adequate convergence (R-hat values below 1.1). Model parameters were analyzed using Bayesian hypothesis testing (95% credible intervals). See Supplemental Information for posterior predictive checks.

## Results

Behavioral analyses of accuracy revealed that the effects of condition and gender on accuracy were not significant. See Supplemental Information for behavioral accuracy and RTs.

### Drift diffusion modeling

**Drift rate.** Analyses of same trials revealed that male participants showed faster drift rates than female participants in both approach (95% posterior probability) and avoidance (96% posterior probability) conditions (see Figure 2). Between-condition comparisons of the same trials, however, revealed no significant differences between the two conditions in either male (62% posterior probability) or female (57% posterior probability) participants.

Analyses of mirror trials revealed no significant gender differences in either the approach or avoidance condition (see Figure 2). Between-condition comparisons of the mirror trials revealed differences between approach and avoidance conditions. Among male (91% posterior probability) and female (93% posterior probability) participants, drift rates were generally faster in the approach than the avoidance condition. These findings suggest that information processing efficiency may be better with approach motivation compared to avoidance motivation, at least on trials in which the objects are mirrored.

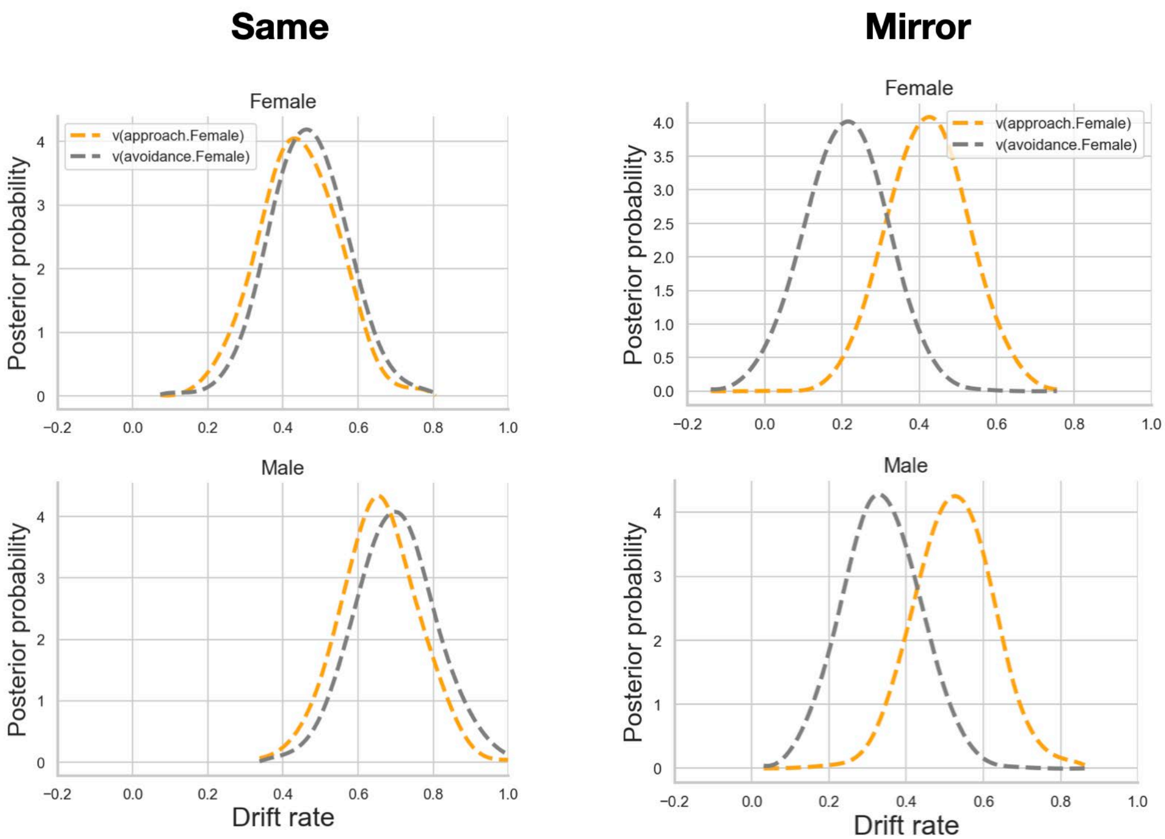



**Figure 2.** Posterior parameter values of drift rates in approach versus avoidance conditions, split by gender and trial type.

**Decision threshold.** Analyses of the same trials revealed no differences between male and female participants in either the approach (72% posterior probability) or avoidance (81% posterior probability) condition (see Figure 3). Between-condition comparisons also revealed no differences between approach and avoidance conditions for either male or female participants.

Analyses of mirror trials revealed significant gender differences in the approach condition but not the avoidance condition (see Figure 3). Interestingly, female participants showed significantly larger decision thresholds than male participants, but only in the approach condition (97% posterior probability; avoidance condition: 77% posterior probability). Between-condition comparisons, however, revealed no significant differences between approach and avoidance conditions for either male or female participants.

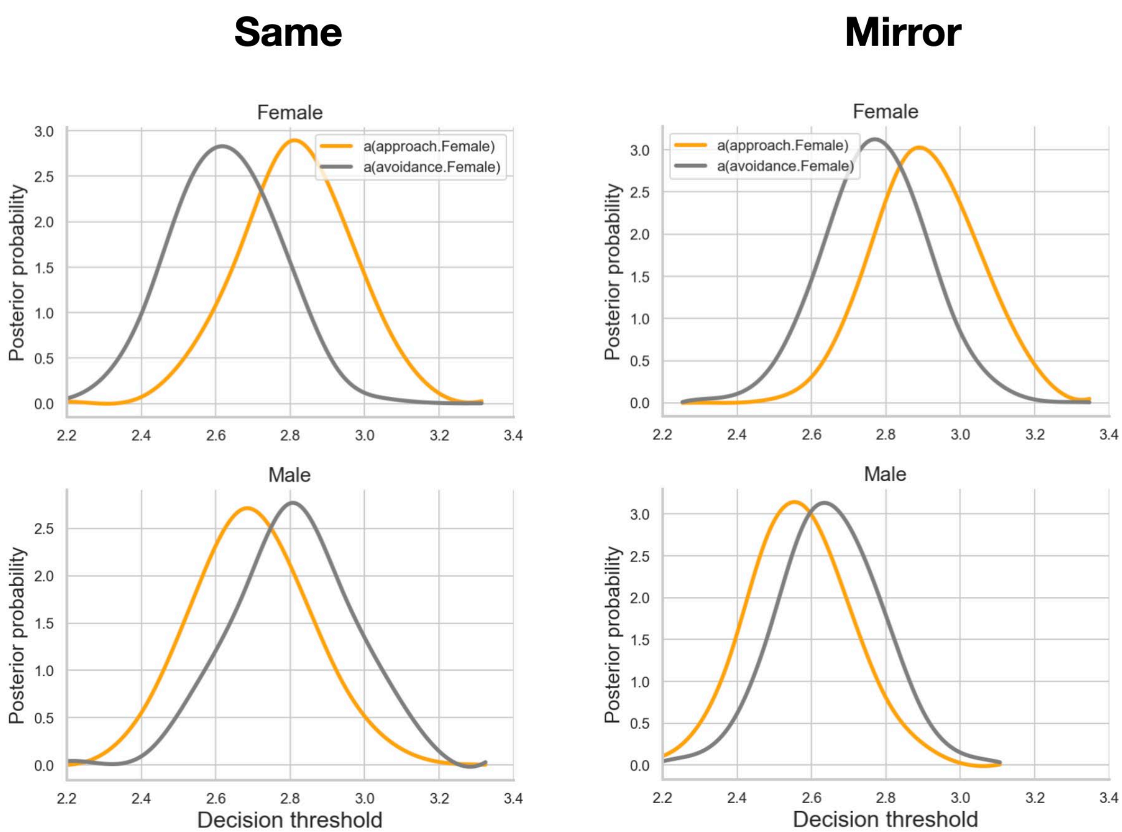



**Figure 3.** Posterior parameter values of decision thresholds in approach versus avoidance conditions, split by gender and trial type.

### Affective Ratings

Due to a small number of rating trials, analyses of participants' ratings were collapsed across same and mirror trials. Participants' mean ratings were analyzed for each of the affective factors as a function of gender and condition. Unless otherwise noted, equal variances were assumed when performing ANOVA analyses. P-values in all post hoc analyses were Bonferroni corrected.

**State anxiety.** Analyses revealed that there were non-equal variances of the levels of anxiety between male and female participants. Thus, we used Welch's one-way ANOVA to examine the effects of gender in each condition. In the approach condition, there was no effect of gender on anxiety ($F$[1, 53.6] = 2.11, $p$ = .153). However, in the avoidance condition, female participants showed higher levels of anxiety than male participants (see Figure 4A; $F$[1, 47.65] = 10.69, $p$ = .002).

**State confidence.** An ANOVA revealed a significant main effect of gender on confidence, $F(1, 109) = 22.44$, $p < .001$, as well as a significant interaction between condition and gender, $F(1, 109) = 9.68$, $p = .002$ (see Figure 4B; condition**:** $F$[1, 109] = 3.82, $p$ = .053). Post hoc analyses revealed that female participants showed significantly lower confidence ratings than male participants, but only in the avoidance condition ($t$[109] = 1.94, $p$ = .055). Additionally, female participants showed higher confidence ratings in the approach than the avoidance condition ($t$[109] = 3.56, $p$ = .003), whereas male participants showed no difference between conditions ($t$[109] = -.83, $p$ > .999).

**State motivation.** There was a significant main effect of condition ($F[1, 109] = 5.93$, $p = .017$), such that ratings were higher in the approach compared to avoidance condition (see Figure 4C; $M_{\text{difference}} = .67$), suggesting that participants in the approach condition were more motivated on the task than participants in the avoidance condition. There was no significant main effect of gender ($F[1, 109] < 1.0$, $p = .856$), or gender by condition interaction ($F[1, 109] = .96$, $p = .330$).

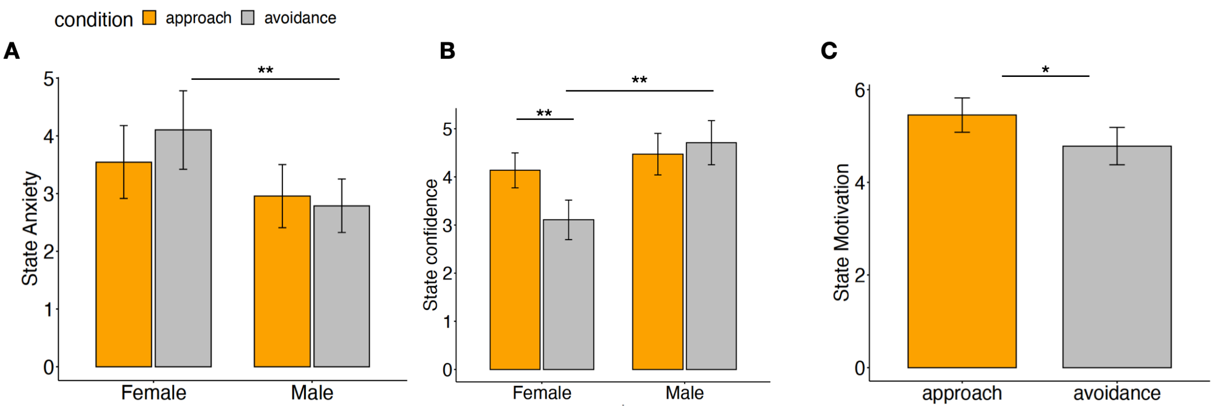



**Figure 4.** Ratings of state anxiety, confidence, and motivation in the approach and avoidance conditions. Unless otherwise indicated, non-significant effects were not shown with asterisks.
* $p < .05$, ** $p < .01$

## Approach-Avoidance System Questionnaire

We were particularly interested in competence expectancy, which is a subscale in the approach/avoidance system questionnaire. Because each of the subscales may vary as a function of condition and gender, separate analyses were performed for each subscale. No significant effects of gender, condition, or gender by condition were found in these two subscales: benefit to the self (when the goal is reached), and threat to the self (when the goal is not reached).

**Competence expectancy.** ANOVAs revealed a significant gender by condition interaction on competence expectancy, $F(1, 109) = 5.99$, $p = .016$ (see Figure 5). Post hoc analyses found that whereas male participants did not differ in their ratings on competence expectancy between approach and avoidance conditions ($M_{\text{difference}} = .04$, $t[109] = .09$, $p > .999$), female participants rated their competence expectancy significantly lower in the avoidance condition compared to the approach condition ($M_{\text{difference}} = -1.8$, $t[109] = -3.53$, $p = .004$).

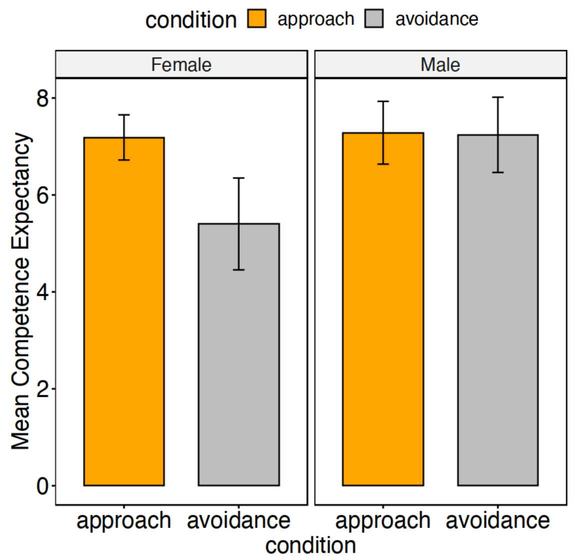



**Figure 5.** Mean competence expectancy for approach versus avoidance condition, split by gender.

### Relations between affective ratings and model parameters

Separate ANOVAs with interaction terms among each of the affective ratings, condition, and gender, were performed to determine whether model parameters of individual participants varied as a function of affective rating, gender, and condition.

### Drift rate

**State anxiety.** There was a significant two-way interaction between anxiety and gender on mean drift rate, $F(1, 104) = 4.26$, $p = .042$ (see Figure 6A). However, the three-way interaction among anxiety, gender, and condition was not significant, $F(1, 104) = 1.75$, $p = .189$. Post hoc trend analyses revealed that male participants' anxiety ratings were negatively associated with drift rate ($b = .10$, 95% CI [-.20, .00]), whereas female participants' anxiety ratings were not ($b = .05$, 95% CI [-.01, .12]). All other interaction effects were not significant (*ps* > .05).

**State confidence.** There was a positive association between confidence and drift rates (see Figure 6B). No other significant effects were found. Trend analyses revealed that confidence was positively associated with drift rates regardless of gender or condition ($b = .09$, 95% CI [.04, .14]).

**State motivation.** No significant motivation by gender by condition interaction effects were found, $F(1, 104) < 1.0$, $p = .863$. No other main effects or interaction effects were significant, suggesting the present results do not show a link between state motivation and drift rates.

### Decision threshold

Neither state anxiety, nor state motivation interacted with gender and approach/avoidance condition, such that three-way interactions were not significant. However, confidence by gender by condition interactions were significant (see Figure 6C). Post hoc analyses revealed that, in the approach condition, male participants' confidence was positively associated with decision thresholds

($b$ = .23, 95% CI[.08, .38]), whereas female participants did not show this association ($b$ = -.14, 94% CI [-.33, .04]). In the avoidance condition, neither gender showed significant associations between confidence and decision thresholds.

Additionally, male participants' slopes were significantly higher in the approach compared to the avoidance condition ($b_{difference}$ = .25, $p$ = .019), suggesting that the relations between confidence and decision thresholds were stronger in the approach than the avoidance condition for males. Female participants' slopes showed no significant differences between approach and avoidance conditions ($b_{difference}$ = -.12, $p$ = .339).

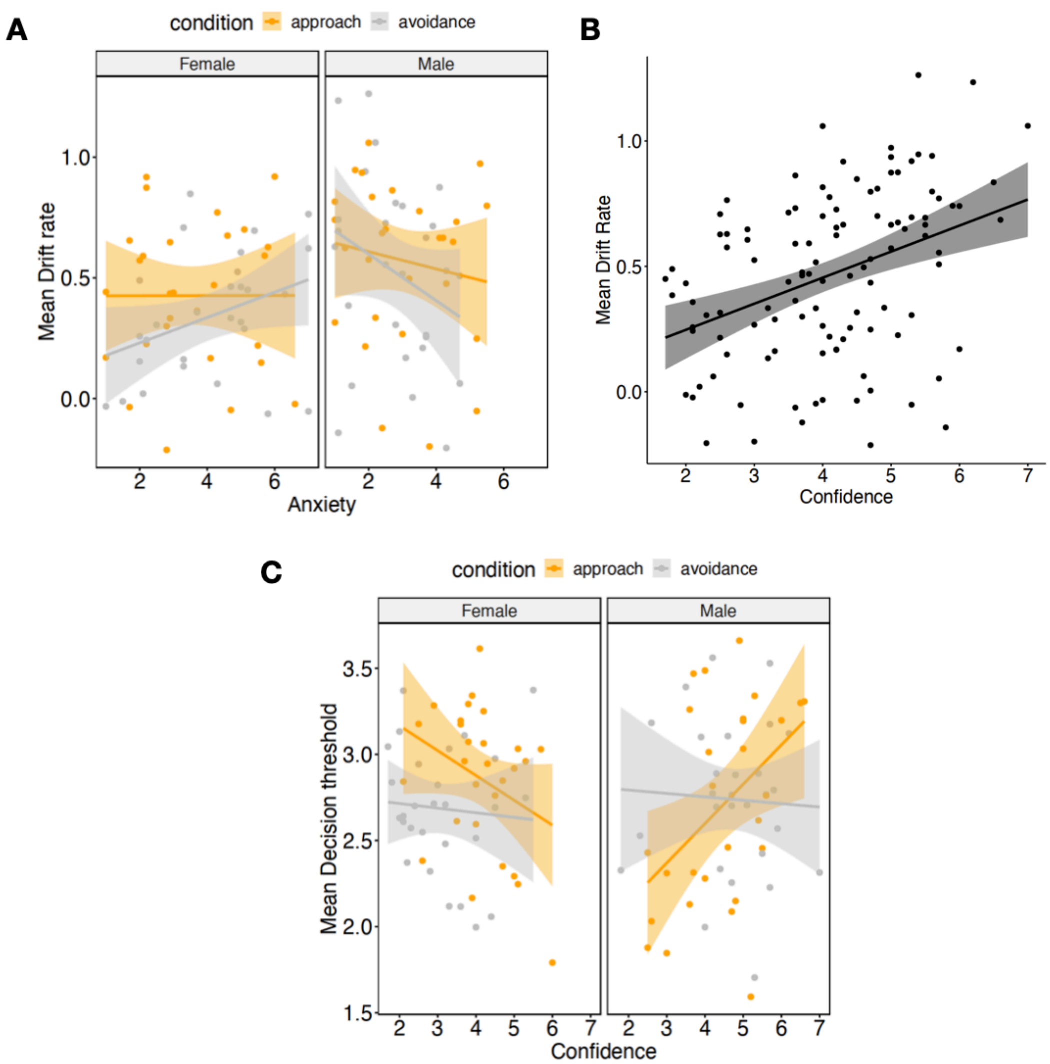



**Figure 6.** Associations between state anxiety and drift rates (A), confidence and drift rates (B), and confidence and decision thresholds (C) as a function of gender and condition.

**Relations between approach indices and model parameters**

We examined the relations between each of the model parameters and competence expectancy, benefit to the self (when the goal is reached), and threat to the self (when the goal is not reached). There was a significant interaction between competence expectancy and condition on drift rate (see Figure 7). Post hoc trend analyses revealed that the association between competence expectancy and drift rate was specific to the approach condition ($b$ = .08, 95% CI [.02, .14]; avoidance condition: $b$ = .02, 95% CI [-.02, 05]).

In terms of decision thresholds, male participants showed a positive association between competence expectancy and decision thresholds in the approach condition ($b$ = .16, 95% CI [.07, 26]), but not the avoidance condition ($b$ = -.08, 95% CI [- .16, .01]). There was a stronger association between competence expectancy and decision thresholds in the approach than the avoidance condition ($\underline{M}_{\text{difference}}$ = .24, $p$ < .001). Female participants, however, showed no significant associations between competence expectancy and decision thresholds in either approach ($b$ = -.08, 95% CI [-.22, .06]) or avoidance ($b$ = -.01, 95% CI [-.06, .08]) condition. Between-gender comparisons also showed that male and female participants significantly differed in their slopes in the approach ($p$ = .006), but not avoidance ($p$ = .121) condition.

All other indices (i.e., benefit to the self; threat to the self; overall approach tendency) did not show effects in relation to drift rates or decision thresholds, nor were their interactions with gender or condition significant.

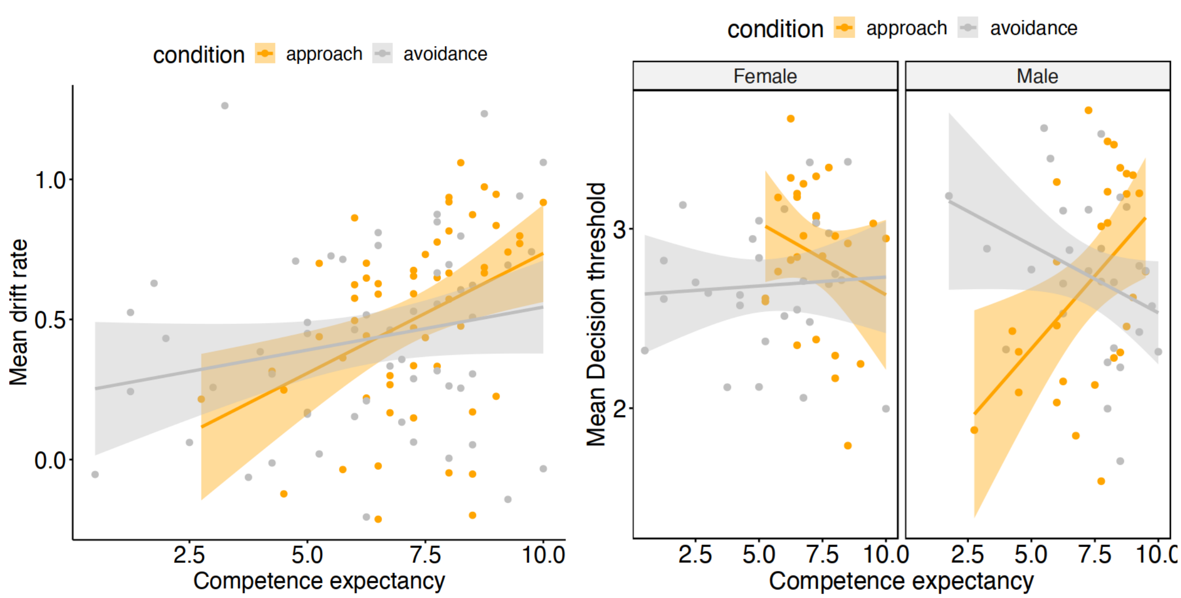



**Figure 7.** Associations between competence expectancy and drift rates/decision thresholds.

## Discussion

The findings of Experiment 1 suggest that information processing and decision making on a mental rotation task changed as a function of motivational and affective states, with gender as a moderating variable.

### Does processing efficiency differ between approach and avoidance conditions?

We hypothesized that drift rates would be faster in the approach condition compared to the avoidance condition. Our results provided evidence for this hypothesis, though there was some variability as a function of trial type. In particular, the increase in drift rates for approach compared to avoidance was stronger on mirror trials than same trials. We speculate that this difference occurs because mirror trials may be more difficult (and, indeed, performance was worse) and may involve holistic processing more than same trials (Hamm, 2004). That is, the holistic processing elicited by approach condition may have been particularly beneficial to mirror trials, which are sensitive to this type of processing and strategy. However, additional evidence is needed to further explore such a possibility.

**Does decision strategy differ between approach and avoidance conditions?**

If approach motivation is associated with information gathering, then greater evidence accumulation should occur under conditions of approach motivation. Conversely, if avoidance motivation is associated with decision caution, then greater evidence accumulation should occur under conditions of avoidance motivation. Interestingly, the present findings do not provide definitive support for either hypothesis, in either male or female participants. There were no differences in decision threshold between approach and avoidance conditions.

One possibility for the lack of an effect is that evidence accumulation does not differ considerably by motivational states on a mental rotation task. Another possibility is that participants may have used a combination of approach and avoidance decision strategies during the tasks, as is common when the benefits of approach and avoidance are both involved in pursuing goals (Ito & Lee, 2016). Specifically, when tasks involve a speed-accuracy tradeoff, monetary gains/losses may be considered alongside the need to respond within a time limit, such that the avoidance of timeout may contribute to avoidance-motivated states in both conditions.

Interestingly, whereas larger decision thresholds in male participants were found in previous research (Liu & Lourenco, 2022), gender differences in decision thresholds were not evident in the present experiment. One exception was in the approach condition (with mirror trials), where female participants showed larger decision thresholds than male participants. This finding contrasts with our previous findings in which female participants showed less response caution, raising an intriguing question about whether approach/avoidance motivation may benefit female participants more than male participants. This issue is discussed further in the next section.

**What is the role of affective states on processing efficiency and decision strategies?**

The present findings showed that the extent of state motivation was higher in the approach than in the avoidance condition. This link provides evidence that the condition manipulation was successful. Although previous research on affective responses have found that women, on average, have higher avoidance motivation than men at the trait level (Carver & White, 1994), we did not find such an effect here, suggesting that this gender difference may be less robust on a mental rotation task.

In the case of mental rotation specifically, previous findings suggest that male and female participants differ in their levels of anxiety and confidence (Alvarez-Vargas et al., 2020; Cooke-Simpson & Voyer, 2007; Liu & Lourenco, 2022). Yet, it was unclear whether approach/avoidance motivation interacted with affective states. Here we found that the effects of approach versus avoidance motivation on both anxiety and confidence differed by gender. Notably, our findings suggest that gender differences in anxiety and confidence appeared to be more pronounced in the avoidance condition. Among women, both state confidence and competence expectancy were higher in the approach condition than the avoidance condition, suggesting that the approach condition may have increased confidence on the current mental rotation task, whereas the avoidance condition did not. This gender-specific effect is particularly interesting. If approach motivation elicited more positive affect than avoidance condition (Gable & Dreisbach, 2021), then both men and women should have shown a boost in confidence. Instead, we found that women were more affected by this manipulation.

With respect to processing efficiency, one highlight of the present results is that a higher level of confidence correlated with faster drift rates. This finding is consistent with our previous experiment without the manipulation of approach/avoidance motivation (Liu & Lourenco, 2022). Additionally, we also found that a higher level of competence expectancy correlated with faster drift rates, at least in the approach condition. With respect to decision strategy, the present results also point to different relations between men and women. We found that a higher level of confidence was associated with greater response caution, but only in male participants and only in the approach condition. The variability in these results raises further questions about how motivational and affective states differ between men and women.

Altogether, the findings of Experiment 1 demonstrate that affective states on a mental rotation task differed according to approach and avoidance conditions. They also show that affective states are differentially associated with processing efficiency and decision strategies. Importantly, participant gender moderated these associations, such that men and women were differentially affected by task condition.

## Experiment 2

Task decisions often involve both approach and avoidance motivation (Corr & McNaughton, 2012; Ito & Lee, 2016). Given the differential effects found between approach and avoidance conditions, one might ask how robust and dissociable these motivational states may be. Findings in affective neuroscience have found that approach and avoidance motivation are affected by contextual factors (Lochbaum & Gottardy, 2015; Yee et al., 2022). Thus, approach and avoidance motivational states may change dynamically as a function of task context. To further investigate the effects of approach and avoidance conditions, we manipulated the presentation order of the approach and avoidance conditions in a within-subject design (i.e., approach-first vs. avoidance-first). If the effects of approach and avoidance motivation are dissociable, then one would not expect order to have an impact on processing efficiency or decision making. We predicted, however, that approach and avoidance motivation are not fully separable and, as such, there would be carryover effects from one condition in the experiment to the other. To assess the potential order effects, we compared drift rate and decision threshold as a function of presentation order (approach-first vs. avoidance-first).

## Method

### Participants

A total of 106 participants were recruited online through *Prolific*: half of the participants completed the approach-first condition, and the other half completed the avoidance-first condition. Eight participants did not finish the study, resulting in a final sample of 98 participants (48 Approach-first [50% females]; 50 Avoidance-first [52% females]). A prior power analysis revealed that the minimal sample size was 88 to account for within-subject and between-subject interaction effects (power = 0.8; alpha = .05). Thus, the current sample size exceeds the required minimum. All participants were right-handed and reported normal or corrected-to-normal vision. All participants reported that their gender identity matched their birth sex. Written informed consent was provided prior to participation. All procedures were approved by the IRB at Emory University.

### Procedure

The mental rotation task was identical to that used in Experiment 1. The only difference concerned the within-, rather than between-, subject manipulation. Instead of assigning participants to either the approach or avoidance condition, participants in Experiment 2 completed both conditions. Half of the participants completed the approach condition first (Approach-first), and the other half completed the avoidance condition first (Avoidance-first). As in Experiment 1, within each condition, participants rated their levels of anxiety/confidence/motivation (randomized order) on 10 randomly selected trials, and, at the end of the study, they completed the Approach/Avoidance System questionnaire.

All participants received the same baseline payment of $2.40 and the study was advertised to have a duration of 15 minutes ($9.60/hour). The incentive structures of approach and avoidance conditions were identical to those in Experiment 1 (approach: earn 0.60 cents/correct trial; avoidance: lose 0.60 cents/incorrect trial). In the Approach-first case, participants received instructions to earn bonus payments before receiving instructions to minimize bonus losses. In the Avoidance-first case, participants received instructions to minimize bonus losses before receiving instructions to earn bonus payments.

### Hierarchical Drift Diffusion Modeling (HDDM)

**Pre-processing of RT data.** Data were trimmed by removing RTs faster than 300 ms and slower than 7500 ms (1.1% of total trials). Both correct and error trials were included in the analyses. Trial-by-trial RT and accuracy data for each participant were inputted into HDDM.

**Model specifications.** As in Experiment 1, parameter estimates consisted of drift rate ($v$) and decision threshold ($a$). Group mean posteriors of the hierarchical model were used to perform statistical analyses. All models excluded 5% of outlier trials and used weakly informative priors by default (Wiecki et al., 2013). Each chain consisted of 6000 samples with the first 200 samples discarded (thinning = 2).

**Model fits.** HDDM was checked for model convergence by inspecting traces of model parameters and the Gelman-Rubin convergence diagnostic statistics (R-hat; Gelman & Rubin, 1992). All models showed adequate convergence (R-hat values below 1.1). Model parameters were analyzed using Bayesian hypothesis testing (95% credible intervals). See Supplemental Information for posterior predictive checks.

## Results

### Behavioral performance

Behavioral performance of accuracy revealed that task order (approach-first versus avoidance-first) interacted with condition (approach versus avoidance) and trial type (same versus mirror), as expected if task order affects visuospatial performance. See Supplemental Information for statistical details. In summary, when the approach condition was presented first, participants' accuracy was higher in the avoidance condition compared to the approach condition. By contrast, when the avoidance condition was presented first, participants' accuracy did not differ between approach and avoidance conditions. Furthermore, accuracy on same/mirror trials differed as a function of task order. Participants' accuracy was higher on mirror trials compared to same trials when the approach condition was presented first (a 4% difference). By contrast, participants' accuracy was higher on the same trials compared to the mirror trials when the avoidance condition was presented first (an 8% difference).

Given that the primary approach of this study is analyses of processing efficiency and evidence accumulation as modeled by drift diffusion modeling, we focus the results section on model parameters in the main text. See Supplemental Information for additional behavioral results.

**Drift diffusion modeling**

We examined how drift rates and decision thresholds differed as a function of task order, condition, trial type, and gender, as well as the interactions among them. We first fitted separate models to examine the main effects of order, condition, and gender within each trial type. We were specifically interested in the interactions of condition by order and the interactions of condition by gender on drift rates and decision thresholds. Thus, we specified condition by order and condition by gender interaction terms in separate HDDM regression models of same and mirror trials. Statistical significance was determined by examining whether the regression coefficient was significantly different from zero (95% credible interval).

**Drift rate**

In terms of carryover effects, a possibility was that the approach-first order would set up approach-oriented motivational states on the subsequent avoidance condition, and similarly, the avoidance-first order would set up avoidance-oriented motivational states on the subsequent approach condition. Consequently, we expected that processing efficiency would be faster for the approach-first than avoidance-first blocks of trials.

Results of HDDM regressions revealed a condition by order interaction for both same (99% posterior probability) and mirror trials (99% posterior probability). However, a condition by gender interaction was only found for same trials (97% posterior probability), not mirror trials (20% posterior probability). Group posteriors were then compared across condition and order.

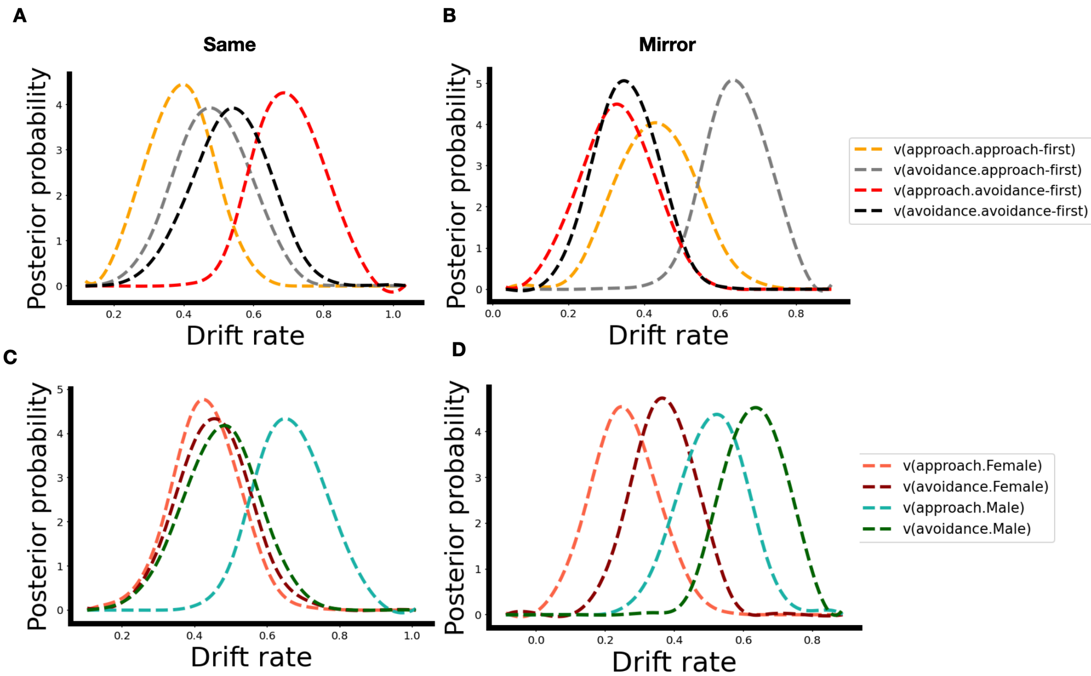



**Figure 8.** Drift rates as a function of order by condition interaction (A & B). Drift rates as a function of gender by condition interaction (C & D).

**Condition by order effects.** We found that, on the same trials, drift rates in the approach condition were faster when the avoidance condition was presented first (see Figures 8A). This aligns with the prediction that avoidance-first may promote analytical/structural thinking, thereby benefiting the same trials. However, drift rates in the avoidance condition were not significantly faster when it was presented first, as compared to when the approach condition was presented first. On the mirror trials, we found that drift rates were faster in the avoidance condition when the approach condition was presented first (see Figure 8B). This is consistent with the idea that the approach-first case may facilitate holistic thinking, thereby benefiting processing efficiency on the mirror trials. Nevertheless, there was no difference in either approach or avoidance conditions when each was presented first.

**Gender by condition effects.** On the same trials, male participants showed significantly faster drift rates than female participants in the approach condition, but not in the avoidance condition (see Figures 8C & D). Male participants in the approach condition also showed moderate evidence of having faster drift rates than in the avoidance condition (92% posterior probability). Female participants, however, showed no such trend. On the mirror trials, gender differences were found in both approach and avoidance conditions (approach: 98% posterior probability; avoidance: 99% posterior probability); male participants had faster drift rates than female participants. Comparisons between approach and avoidance conditions, however, did not reveal significant differences in drift rates in either male or female participants.

**Decision threshold**

Results of HDDM regressions revealed that, on both same and mirror trials, there was a significant condition by order interaction on decision thresholds (99% posterior probabilities; see Figures 9A & B). However, group mean comparisons for each trial type did not reveal significant differences between approach and avoidance conditions in either the approach-first or avoidance-first case.

No gender by condition interaction was found (see Figures 9C & D; same: 86% posterior probability; mirror: 58% posterior probability), nor was there a main effect of gender (61% posterior probability).

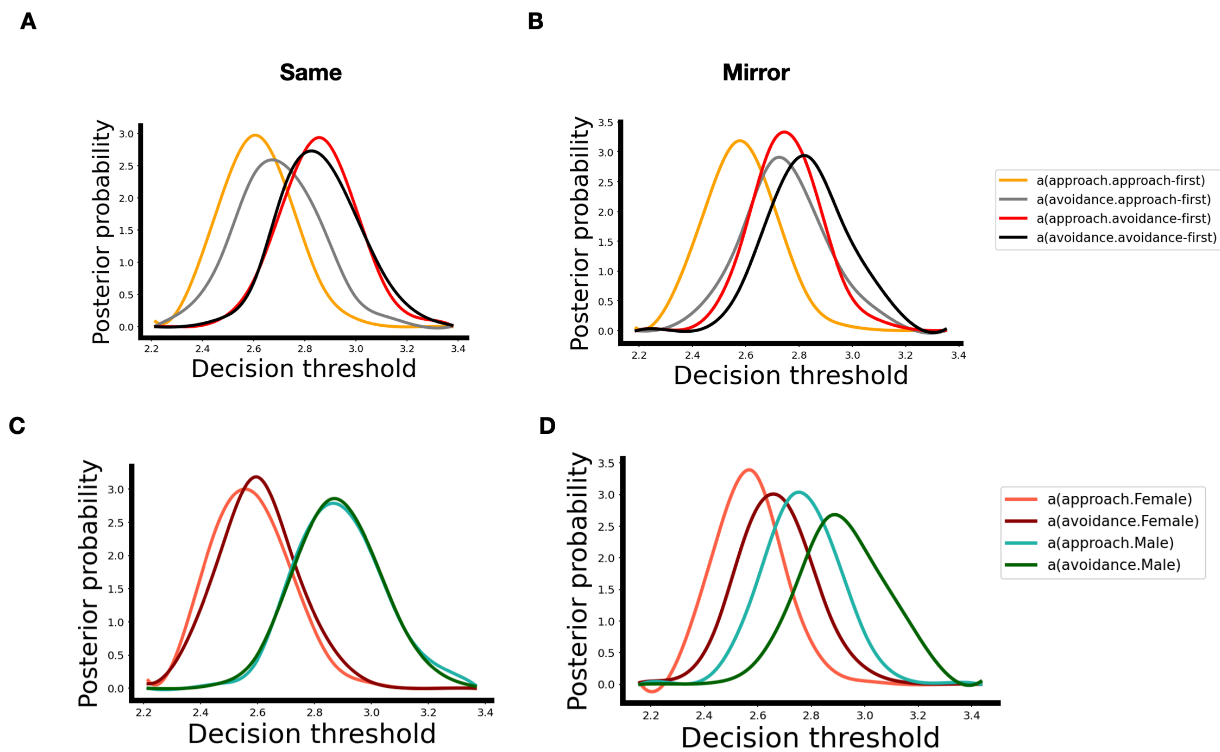



**Figure 9.** Decision thresholds for the order by condition interaction (A & B). Decision thresholds plotted by gender and condition (C & D).

## Affective Ratings

As in Experiment 1, ratings for both the same and mirror trials were collapsed. To account for the within-subject design of Experiment 2, mixed ANOVAs, with order and gender as between-subject factors, and condition as a within-subject factor, were performed on individual participant's mean ratings of anxiety, confidence, and motivation.

**State anxiety.** Mixed ANOVAs revealed a significant main effect of condition ($F[1, 94]$ = 21.56, $p$ = .012), such that mean ratings of anxiety in the approach condition were lower than those in the avoidance condition ($M_{difference}$ = .39). No effects of gender or interactions were significant, suggesting state anxiety was lower in the approach than the avoidance condition regardless of task order.

**State confidence.** Mixed ANOVAs revealed significant main effects of condition ($F[1, 94]$ = 13.19, $p$ = .013) and gender ($F[1, 94]$ = 11.56, $p < .001$). Mean ratings of confidence in the approach condition were higher than those in the avoidance condition ($M_{difference}$ = .29), and female participants had lower ratings of confidence than male participants ($M_{\text{difference}}$ = - .86). No interaction effects were found (*ps* > .05). Again, suggesting that the effects were stable regardless of task order.

**State motivation.** Mixed ANOVAs revealed a significant 2-way interaction between task order and condition on state motivation ($F$[1, 94] = 9.76, $p$ = .002). State motivation was rated significantly higher in the approach condition than the avoidance condition when the approach condition was presented first (approach-first), $M_{\text{difference}}$ = - .43, $t$[94] = 3.42, $p$ = .006. Unlike anxiety and confidence, there was order effect, such that participants were more motivated in the approach condition than avoidance condition, but this effect was not evident when avoidance condition was presented first. All other comparisons were not significant (*ps* > .05).

In summary, anxiety and confidence varied as a function of condition. Participants reported lower levels of anxiety and higher levels of confidence in the approach condition than the avoidance condition, suggesting that the approach condition may have had an effect on enhancing positive affective states. For state motivation, the effects varied as a function of task order. Participants reported greater motivation in the approach condition, but only when the approach condition was presented first. The finding suggests that an avoidance-first order may negatively impact the approach motivation instructions, such that participants' lower motivation in the avoidance condition impacts state motivation during the approach condition.

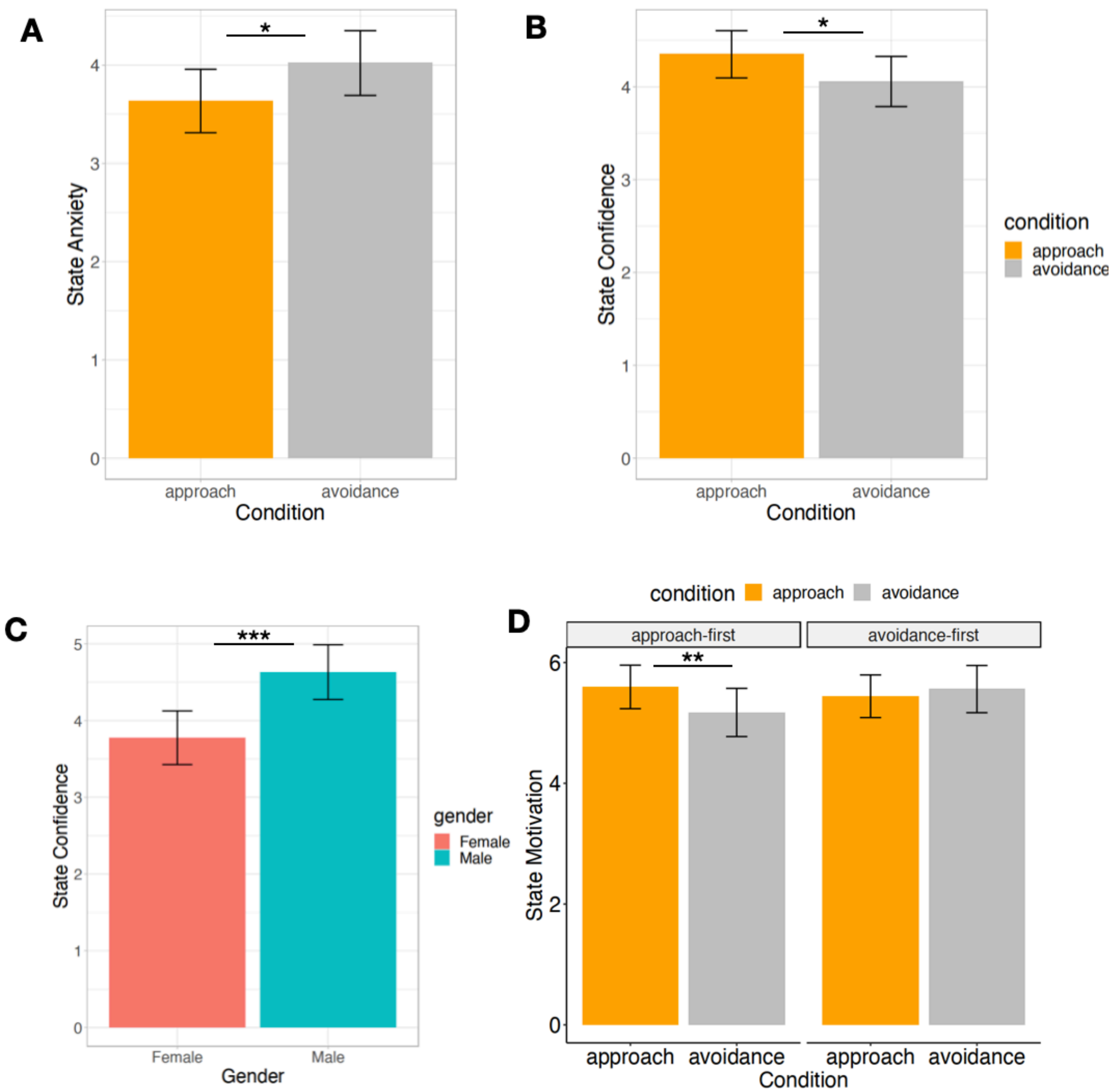



**Figure 10.** Mean ratings of state affective factors. * $p < .05$, ** $p < .01$, *** $p < .001$.

## Approach-Avoidance System Questionnaire

We performed ANOVAs on each of the subscales: competence expectancy, benefit to the self when the goal is reached, and threat to the self when the goal is not reached. Because the approach-avoidance system questionnaire was completed at the end of the approach-first case or avoidance-first case, we were not able to compare how subscales differed across approach versus avoidance conditions. Nevertheless, we examined the effects of task order, gender, and their interactions.

**Competence expectancy.** An ANOVA revealed a significant effect of gender on competence expectancy, $F(1, 94) = 4.37$, $p = .040$. Female participants rated their competence expectancy significantly lower than male participants ($M_{\text{difference}}$ = - .83). No order or order by gender interaction effects were significant ($ps > .05$)

**Threat to the self.** An ANOVA revealed a significant main effect of gender on threat to the self $F(1, 94) = 7.60$, $p = .007$, such that female participants rated their threat to the self significantly higher than male participants ($M_{\text{difference}} = 1.32$), suggesting that female participants concerned more about failing to achieve task goals than male participants. No order or order by gender interactions effects were significant.

ANOVA on the subscale of benefit to the self revealed no significant main effects of gender, or order, or significant interactions.

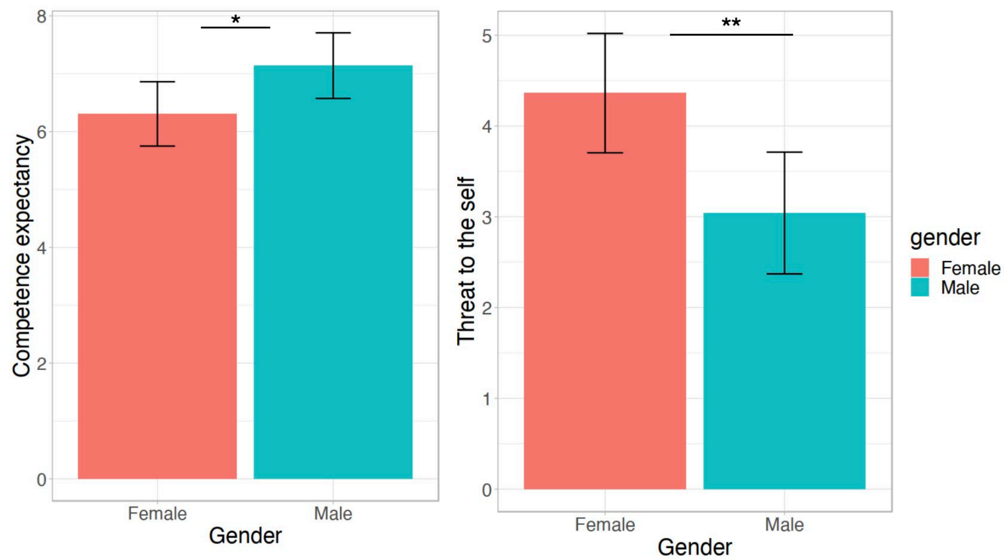



**Figure 11.** Gender differences of the competence expectancy and threat to the self. * $p < .05$, ** $p < .01$.

**Relations between affective ratings and model parameters**

Model parameters (mean drift rates and decision thresholds) were extracted for individual participants. As above, we were interested in examining the relations between model parameters and affective ratings. We performed ANOVAs to examine whether model parameters varied as a function of affective rating, gender, order, and condition and their interactions.

**Drift rate**

**State anxiety.** There was a significant two-way interaction between anxiety and order on drift rates, $F(1, 180) = 5.77$, $p = .017$. No other interactions were significant (though the 3-way interaction among anxiety, gender, and order was marginal, $F[1, 180] = 3.33$, $p = .069$). Nevertheless, because we were interested in how male and female participants' drift rates might change as a function of anxiety and order, we performed trend analyses for both genders. Trend analyses revealed that, for male participants, there was a difference between approach-first and avoidance-first, such that higher levels of anxiety were associated with slower drift rates in the approach-first case (see Figure 12A; $b = -.11$, 95% CI[-.18, -.03], but not in avoidance-first ($b = .05$, 95% CI [-.02, -

.11]). Female participants did not show significant associations between anxiety and drift rate (approach-first: $b$ = -.05, 95% CIs [-.13, .02]; avoidance-first: $b$ = -.03, 95% CIs [-.10, .03).

**State confidence.** There were no significant interactions among anxiety, gender, condition, and order on drift rates (all $ps > .05$).

**State motivation.** There was a significant two-way interaction among order and anxiety on drift rates (see Figure 12B; $F[1, 180] = 12.40$, $p = .001$), but the motivation by order by gender interaction was not significant ($F[1, 180] < 1.0$, $p = .487$). Post hoc trend analyses revealed that both participants' state motivation was significantly associated with drift rates in the approach-first case ($b$ = .12, 95% CI[.06, .17]), but not in the avoidance-first case ($b$ = -.05, 95% CI[-.12, .02]). These findings suggest that higher levels of motivation are associated with faster drift rates when approach motivation is experienced first, regardless of gender. However, the fact that only the approach-first showed such effects suggests a detrimental effect resulting from avoidance motivation when it is experienced at the beginning of the task.

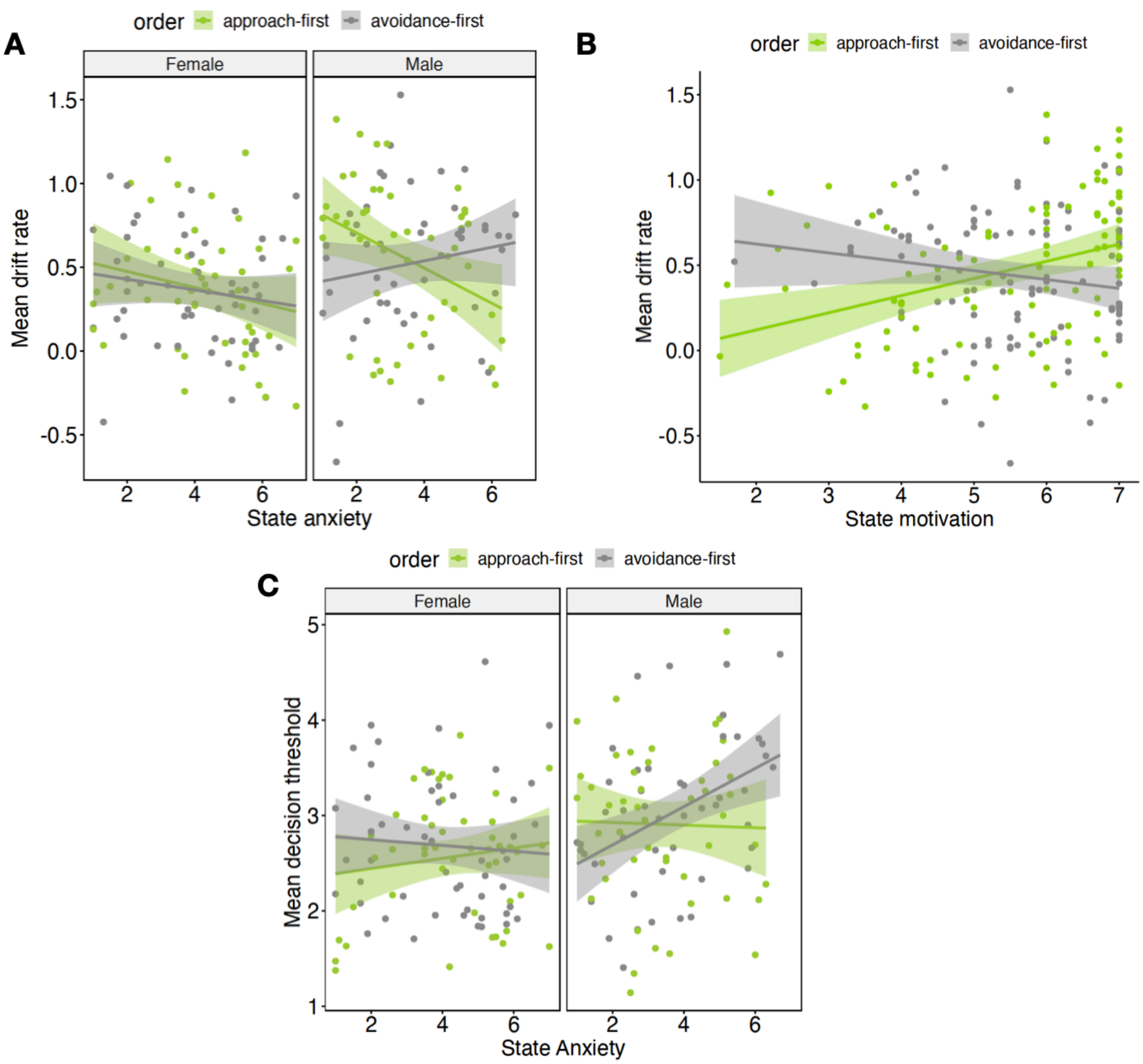


**Figure 12.** Associations between state anxiety and drift rates (A), state motivation and drift rates (B), and between state motivation and decision thresholds (C) by gender and task order.

### Decision threshold

**State anxiety.** There was a significant three-way interaction between state anxiety, gender, and order on decision thresholds (see Figure 12C; $F[1, 180] = 5.79$, $p = .017$). Post hoc trend analyses revealed that male and female participants differed in the avoidance-first case, but not the approach-first case. Specifically, in the avoidance-first case, higher levels of anxiety were associated with larger decision thresholds among male participants ($b = .19$, 95% CI [.06, .31]), but not female participants ($b = -.05$, 95% CI [-.17, .06]. Neither gender showed significant associations between anxiety and decision thresholds in the approach-first case.

**State confidence.** There were no significant interactions between state confidence, gender, condition, and order on decision thresholds (all *ps* > .05).

**State motivation.** There were no significant interactions between state motivation, gender, condition, and order on decision thresholds (all *ps* > .05).

### Relations between approach indices and model parameters

**Competence expectancy.** There was a significant two-way interaction between competence expectancy and order on drift rates (see Figure 13; $F [1, 90] = 8.29$, $p = .005$). Post hoc trend analyses revealed a significant relation between competence expectancy and drift rate in the approach-first ($b = .07$, 95% CI [.02, .13]), but not the avoidance-first ($b = -.04$, 95% CI [-.11, .02]) case. No other gender or order-related interaction effects were significant.

**Benefit to the self.** There was a significant two-way interaction between benefit to the self and order on drift rates (see Figure 13; $F [1, 90] = 8.18$, $p = .005$). Post hoc trend analyses revealed a significant relation between benefit to the self and drift rate in the avoidance-first (see Figure 13; $b = -.07$, 95% CI [-.13, .-02]) but not the approach-first ($b = .04$, 95% CI [-.01, .09]) case. No other gender or order-related interaction effects were significant.

Regarding decision thresholds, no significant interaction effects between each of the subscale and order on decision thresholds were found (all *ps* > .05).

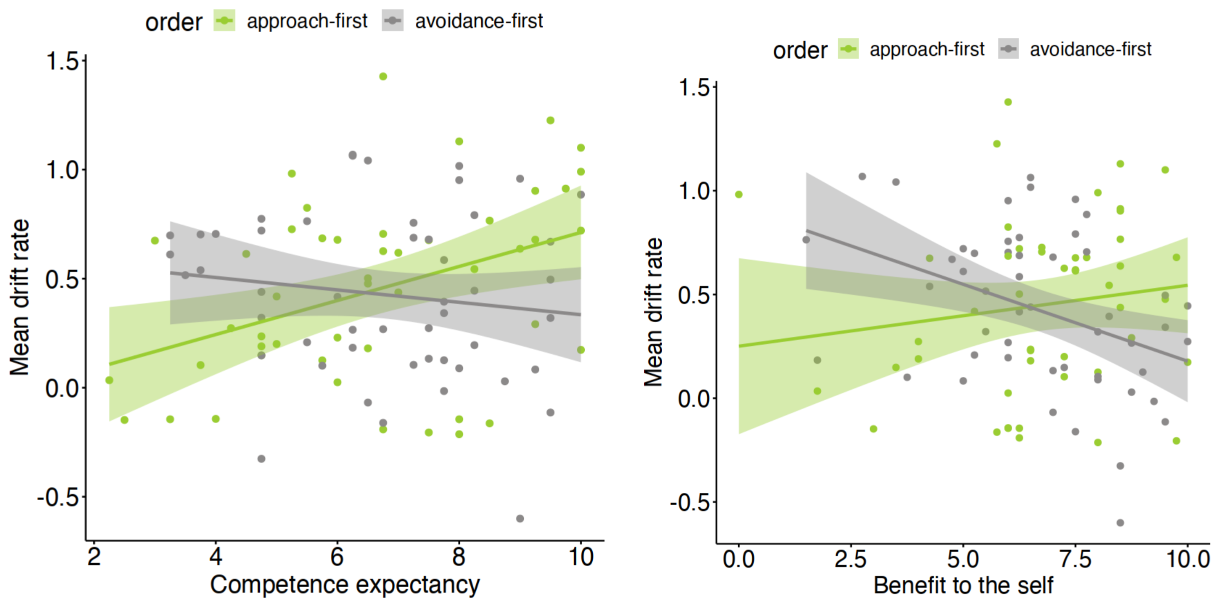



**Figure 13.** The associations between competence expectancy (A) and benefit to the self (B) on drift rates as a function of task order.

## Discussion

In Experiment 2, we manipulated the order of the condition (approach-first versus avoidance-first) to test the role of motivational states situated in specific task contexts.

### Does processing efficiency differ across task order?

The present findings suggest that processing efficiency did vary by task order (and trial type). We found that, on the same trials, drift rates were faster in the approach condition when the avoidance condition was presented first. On the mirror trials, drift rates were faster in the avoidance condition when the approach condition was presented first. These findings provide support that motivational states may be situated in the task context and their effects have impacts on visuospatial information processing.

Particularly relevant to spatial tasks is whether processing efficiency shows differential effects according to trial type. In Experiment 1, we showed that the approach motivation condition benefited processing efficiency for mirror trials more than same trials. The findings from Experiment 2 provide converging evidence in that the effects of condition and order were both dependent on trial type. In fact, the order effect of motivational states in the same trials was opposite those in the mirror trials. We speculate that, on the same trials, the avoidance-first case may have primed the subsequent approach condition to be more avoidance-oriented, which, in turn, may have facilitated processing efficiency on the same trials where structural thinking is beneficial (Paschke et al., 2012). By contrast, the approach-first case may have primed the subsequent avoidance condition to be approach-oriented, which, in turn, may have facilitated processing efficiency on the mirror trials where holistic thinking is preferable (Hamm et al., 2004).

### Does decision strategy differ across orders?

In contrast to processing efficiency, the findings of Experiment 2 did not show differences in decision thresholds across task order, suggesting that participants in Experiment 2 did not substantially vary their decision strategies, as in Experiment 1. Altogether, the results from these two experiments suggest little, if any, effect on decision strategies that may arise according to approach versus avoidance motivation.

Variables that can potentially affect participants' decision thresholds include time pressure, subjective perception of incentives, and the amount of caution and effort (Bogacz et al., 2010; Yee et al., 2022). For example, previous research suggests that participants adjust their decision thresholds to obtain the maximum bonuses (Bogacz et al., 2010). Accordingly, a lack of change in decision thresholds in our study may have reflected that the participants adopted similar adjustments to obtain the maximum bonuses to either approach or avoidance conditions. However, findings from our unpublished results (see Chapter 2) suggest that time constraints shifted decision thresholds from greater to lesser evidence accumulation. Thus, it is likely that because both approach and avoidance conditions had the same time constraint, participants may have adopted similar degrees of speed-time tradeoff. However, the interaction between task order, motivational states, and time constraints remains unknown. Future research may manipulate the amount of time constraints in addition to motivational states to examine such interactions more closely.

**What is the role of affective states on processing efficiency and decision strategies?**

With respect to affective states, our findings appeared to largely replicate the results in Experiment 1, though gender did not interact with condition in the present experiment. We found lower levels of state anxiety and higher levels of state confidence in the approach than the avoidance condition, regardless of task order and gender. For state motivation, a higher level of motivation was found in the approach than avoidance condition, but only in the approach-first case. Thus, despite the potential carryover effects from task order, it appears that affective states are relatively stable when comparing approach versus avoidance conditions.

However, the role of affective states on processing efficiency and decision strategies changed as a function of task order. With respect to processing efficiency, higher competence expectancy was associated with faster drift rates in the approach-first, but not the avoidance-first, case, regardless of condition. Perhaps approach-first primed approach-oriented states across the experiment; thus, the observed positive association is theoretically consistent with the positive association observed between approach motivation and drift rates in Experiment 1. In addition, higher state anxiety and motivation were both positively associated with drift rates in the approach-first case only, though gender moderated anxiety. These findings, again, are consistent with previous findings (Study 2; Liu & Lourenco, 2022). At least in the approach-first case, the associations between affective ratings (anxiety and motivation) were relatively converging across experiments.

The avoidance-first case, however, requires further exploration regarding what affective states contribute to changes in model parameters. Nevertheless, the current associations suggest that greater state anxiety was associated with larger decision thresholds, at least among male participants. Future experiments should manipulate approach/avoidance motivation to better understand gender differences in decision thresholds. There are open questions as to why gender moderated the relations between affective states and model parameters.

## General Discussion

The present study examined the interplay between motivation and affective states on a mental rotation task. In Experiment 1, we manipulated motivational states (approach or avoidance) through task incentives and assigned participants to either condition. In Experiment 2, all participants experienced both task incentives but in a different order (approach-first vs. avoidance-first). In both experiments, we used drift diffusion modeling to dissociate between processing efficiency (indexed by drift rates) and decision strategy (indexed by decision thresholds) on mental rotation. We then examined how self-reported affective states (state anxiety, confidence, and motivation) related to the two model parameters across task conditions and gender. Our findings suggest that processing efficiency and decision strategy are differentially linked to distinct motivational and affective states, with gender playing a moderating role in these relations. These findings shed light on the computational mechanisms underlying the interplay between motivation and affect on spatial tasks.

### Processing efficiency, but not decision strategy, varies as a function of motivational states

Extant studies on motivation have shown that rewards affect a wide range of perceptual and cognitive processes (Aarts et al., 2011; for review, see, Pessoa, 2009). However, there are open questions about whether task enhancement is due to boosts in information processing via attentional control, or to increased goal-directed behaviors (e.g., effort or caution) during the decision stage (Yee et al., 2022). Recent work has demonstrated that processing efficiency and decision strategy, the variables of interest in the present study, can be effectively tested using a formalized computational framework (e.g., DDM; Bogacz et al., 2006).

Our findings suggest dissociable influences of motivational states on processing efficiency, but not decision strategy. Specifically, in Experiment 1, processing efficiency changed as a function of motivational state. In Experiment 2, processing efficiency changed as a function of the order of motivational states. However, decision strategies, in both experiments, were relatively unchanged by motivational state. Altogether, these findings are consistent with motivational effects on task performance that are primarily regulated via information processing. This means that the rate of evidence accumulation (drift rate) may be influenced by strategic control of attention, such that increases of attention on stimuli facilitates information processing. Notably, we found evidence that processing efficiency was enhanced under approach motivation compared to avoidance motivation (Experiment 1), and when approach motivation was presented first compared to when presented second (Experiment 2). These findings generally align well with the idea that approach-oriented motivation may be associated with holistic processing and attentional flexibility (Fredrickson, 2013; Fredman & Foster, 2010).

Recent theoretical work has suggested that the effects of motivation on information processing and decision strategy should be considered in the context of task demands (Yee et al., 2022). Specifically, this view challenges the assumption that the motivation effects on cognitive processing are non-specific. The present findings demonstrate that the influence of motivational state varies according to trial type: same vs. mirror trials. This highlights the importance of considering the specific spatial processes involved in information processing. For example, mirror trials may involve an additional processing step of "flipping" stimuli (Hamm et al., 2004). In addition, the discrimination between mirror trials and same trials has distinct neural mechanisms (Martinaud et al., 2016). Given that the processing of same and mirror trials diverges early in perceptual encoding

(Paschke et al., 2012), these differences warrant closer examination of how motivational states interact with context during mental rotation.

Our present results did not show changes in decision thresholds through task incentives, as found in studies with other cognitive tasks (e.g., numerical discrimination; Dix & Li, 2020). However, it is worth noting that motivation is indeed associated with different strategies in cognitive effort allocation and decision caution (Leng et al., 2021), influencing decision thresholds. Theoretical models such as Expected Value of Control (EVC) predict that drift rates and decision thresholds vary based upon expected benefits (Shenhav et al., 2017). Moreover, individuals vary in their sensitivity and intensity to rewards (Yee et al., 2022) and, as such, decision caution may be influenced by other, yet unknown, factors. Even though our present study did not explicitly measure individuals' sensitivity to external rewards (e.g., bonuses) or internal rewards (e.g., feedback), the data we collected from individuals' affective states provide valuable insights into how processing efficiency and/or decision thresholds are associated with affective states.

**Affective states and their associations with processing efficiency and decision strategy**

Recent research has highlighted how DDM can benefit the understanding of affective states on decision-making (Roberts & Hutcherson, 2019), but little is known about how such interactions affect performance on mental rotation tasks, where large gender and individual differences exist. The present findings suggest that state anxiety, confidence, and motivation have distinct associations with individuals' processing efficiency and decision strategy.

With respect to processing efficiency, the present findings align well with our prior work (Chapter 3; Liu & Lourenco, 2022), suggesting that state confidence and motivation are associated with faster processing efficiency, whereas anxiety is associated with slower processing efficiency. These relationships, however, show some differences depending on gender, motivational state, and task order (i.e., approach-first vs. avoidance-first). Among these affective states, increased anxiety and slower processing efficiency are well-established via attentional control theory (ACT) (Eysenck et al., 2007). According to ACT, anxiety is associated with stimulus-driven (bottom-up) attention that competes with goal-directed (top-down) attention, thereby reducing processing efficiency. As avoidance motivation may induce stimulus-driven attention (for review, see Lourenco & Liu, 2023), the interaction between motivational states and anxiety may explain why a negative relation was found between anxiety and drift rates in the avoidance condition (Experiment 1).

With respect to decision strategy, our data suggest that state confidence and confidence expectancy towards task goals are associated with decision thresholds, with differences between genders and conditions. Regarding confidence, these findings are in line with studies demonstrating that increased decision thresholds are associated with greater evidence accumulation (Hauser et al., 2017), as well as our previous work (Liu & Lourenco, 2022). However, these findings seem to conflict with studies where confidence was evaluated as predicting subsequent decision thresholds (Desender et al., 2019). Interestingly, such associations were only found in the approach-first case in Experiment 2. Future research should consider applying the EVC model to examine how confidence and motivation might influence expected benefits. Notably, further examination is needed on the impact of top-down approach/avoidance appraisals on downstream decision thresholds (Mohanty et al., 2023).

*Implications for gender differences*

Finally, our findings suggest that gender played a moderating role on mental rotation performance, such that the effects of motivational and affective states varied between male and female participants. These findings indicate that understanding gender-specific effects on processing efficiency and decision thresholds may help to shed light on the gender differences on mental rotation tasks. Whereas the field's focus has largely been on differences of affective factors at the trait level, our work highlights the dynamic role of motivational and affective states in influencing the magnitude of gender differences. Insights from our work could be relevant for understanding spatial processing and decision-making, particularly under high stakes conditions (Starcke & Brand, 2012).

**Supplemental Information for "The effects of motivational and affective states on spatial processing and decision strategies "**

## Experiment 1

### Behavioral performance

Preliminary analyses comparing the accuracy of same and mirror trials found a significant effect of trial type on accuracy. Specifically, participants were more accurate on same trials compared to mirror trials ($M_{\text{difference}}$ = .06, $t$[224] = 2.48, $p$ = .015). Given these results, we decided to analyze same and mirror trials separately in subsequent analyses.

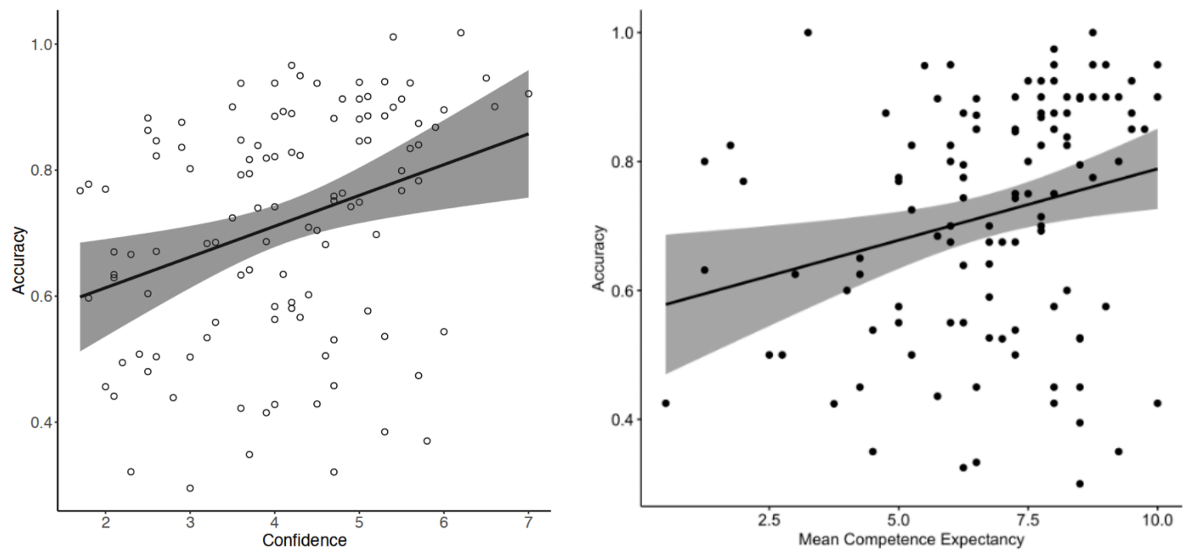
**Accuracy.** ANOVAs examined the effects of condition, gender, and their interaction on mean accuracy for same and mirror trials. Whereas there was no main effect of condition on accuracy on same trials, $F(1, 109) = 0.047$, $p = .835$, there was a marginal main effect of condition on mean accuracy on mirror trials, $F(1, 109) = 3.85$, $p = .052$. Pairwise comparison found that accuracy in the approach condition was marginally higher than accuracy in the avoidance condition ($M_{\text{difference}}$ = .08, $t$[109] = 1.96, $p$ = .052).

For same trials, there was a marginal main effect of gender on accuracy, $F(1, 109) = 2.91$, $p = .091$, but mirror trials showed no such effect ($p$ = .387). Both same and mirror trials found no significant interaction effects between condition and gender (same: $F$[1, 109] = .044, $p$ = .83; mirror: $F$[1, 109] = 0.002, $p$ = .965).

**RTs.** ANOVAs revealed no significant main effects of condition (same: $F$[1, 109] = .111, $p$ = .740; mirror: $F$[1, 109] = .312, $p$ = .965) or gender (same: $F$[1, 109] =2.00, $p$ = .160; mirror: $F$[1, 109] = 1.88, $p$ = .173) on RTs for both same and mirror trials. No gender by condition interaction effects were found.

### Relations between affective ratings and overall accuracy

Multiple regression analysis with anxiety, confidence, and motivation, controlling for gender and condition found that confidence was positively associated with overall accuracy (see Supplemental Figure 1; $b$ = .05, $p$ =.004), but anxiety and motivation showed no significant associations ($ps$ > .05).




**Supplemental Figure 1.** The associations between confidence and accuracy (left) and competence expectancy and accuracy (right).

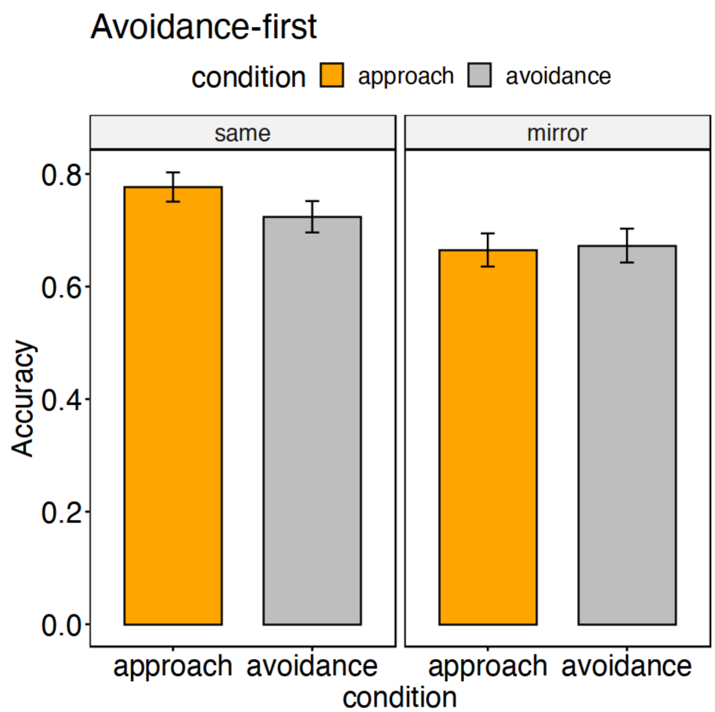
### Experiment 2

Linear mixed model revealed a significant order by condition interaction ($p < .001$), a significant order by trial type interaction ($p < .001$), and a significant trial type by condition interaction ($p = .003$). Regarding gender-related interactions, a significant trial type by gender interaction was also found ($p = .024$). Given these interaction effects found here, we did not aggregate order and trial type for subsequent analyses.

### Behavioral accuracy

**Approach-first.** Mixed model with trial type, condition, gender, and their interactions as fixed factors, participant with random intercept, was examined for their effects on accuracy. Results revealed a significant main effect of condition ($F[1, 3694] = 12.78$, $p < .001$), such that accuracy in the avoidance condition was higher than the approach condition (difference = .05, $p < .001$). There was also a significant main effect type ($F[1, 3694] = 7.39$, $p < .001$), such that same trials scored lower than mirror trials (difference = -.04, $p = .006$). No significant trial type by condition or type by gender interaction effects were found ($ps > .05$).

**Avoidance-first.** We included the same variables in a mixed model, as in the approach-first condition. Results revealed a significant interaction effect between trial type and condition ($F[1,3855] = 5.24$, $p = .022$). Post hoc comparisons of the interaction effect revealed that accuracy on the approach condition was higher than avoidance condition on the same trials (see Supplemental Figure 2; $M_{\text{difference}} = .05$, $p = .014$), but no differences were found on the mirror trials ($M_{\text{difference}} = .01$, $p > .999$). Also, accuracy on the same trials were higher than the mirror trials in both the approach ($M_{\text{difference}} = .11$, $p < .001$) and avoidance condition ($M_{\text{difference}} = .05$, $p = .032$). No other interaction effects were significant ($ps > .05$). These results suggest that that the boost from the approach condition may be specific to the same trials following the avoidance condition.




**Supplemental Figure 2.** Mean accuracy for approach versus avoidance condition in the avoidance-first order.

# Chapter 5 - General Discussion

Despite extensive research examining gender differences in mental rotation performance, much remains elusive about the underlying mechanisms of these differences. A substantial amount of research has focused on how men and women differ in their behavioral accuracy, and the factors that may affect accuracy. However, it remains unknown whether gender differences occur during rotational-stage processes, decision-stage processes, or both, as information processing and decision-making are not isolated within the behavioral data. Moreover, affective factors are known to mediate gender differences in accuracy, but it has remained unclear how these factors might impact processing efficiency and/or decision-making on mental rotation tasks.

The evidence presented in the current dissertation suggests that (1) spatial information processing and decision-making are dissociable by drift diffusion modeling; (2) spatial information processing and decision-making are differentially impacted by affective and motivational states; and (3) gender differences in processing efficiency and decision-making are influenced by affective factors.

In Chapter 2, I found gender differences in information processing and decision thresholds under conditions where the task instructions emphasized speed but not when the task instructions emphasized accuracy. The findings of this study suggest that time pressure, which may induce changes in affective states, is associated with slower information processing and reduced evidence accumulation, with women more negatively impacted than men. In Chapter 3, I found that anxiety, confidence, and motivation differentially impact information processing and decision strategy. Importantly, confidence and motivation served as mediating and moderating factors to gender differences in model parameters (Liu & Lourenco, 2022), suggesting that affective states accounted for gender differences on mental rotation tasks. Finally, in Chapter 4, I found that distinct motivational states (approach versus avoidance) are associated with differences in state anxiety, state confidence, and state motivation, influencing spatial information processing and decision strategy. Moreover, participant gender modulated these associations, suggesting differential impacts of affective and motivational states on the mental rotation performance of men and women. Together, the present studies provide mechanistic explanations of information processing and decision-making underlying individual and gender differences in mental rotation performance.

## Decomposition of mental rotation task processes using DDM

Visuospatial decisions on mental rotation tasks involve multiple stages (Heil & Rolke, 2002). Using drift diffusion modeling, I proposed that the mechanisms of mental rotation could be better understood by assuming that information is noisily accumulated to reach a decision. Drift diffusion modeling is an ideal computational modeling approach to decompose mental rotation tasks, separating information processing related to object manipulation (rotation) and decision-stage mechanisms.

One of the converging findings across the present studies was that DDM effectively captures processing efficiency, as evidenced by the decrease in drift rates with increasing angular disparities. Our results demonstrated that the processing efficiency was slower with increased difficulty, consistent with findings from tasks such as numerical discrimination (Dix & Li, 2020; Zhang & Rowe, 2014), as well as tasks that have examined angular effects in the context of visual search (Larsen, 2014). Importantly, drift rates appear to explain the angular disparity effect commonly found in the literature (Searle & Hamm, 2017).

With respect to evidence accumulation, it appears that decision thresholds showed more variability across studies. In particular, the experiments described in Chapter 2 showed little differences in decision thresholds across angular disparities. However, the experiments described in Chapter 3 showed a linear increase in decision thresholds as a function of disparity. As decision thresholds may reflect decision caution, our data suggest that such a response strategy may be subject to influences from factors independent of angular disparities, in contrast to the typical effects found with RTs. Thus, decision thresholds may not only offer a mechanistic explanation for how participants reach decisions on mental rotation tasks, but they may also provide a metric for understanding the decision-making variability as a function of external influences (e.g., cognitive load).

A limitation of the present work is that the hierarchical drift diffusion modeling (Wiecki et al., 2013) is largely restricted to data from 2-alternative forced choice tasks, such as those generated by chronometric mental rotation tasks. However, larger gender differences are typically observed on the paper-and-pencil version of mental rotation tasks (Peters, 2005; Voyer et al., 1995). These tasks involve multi-choice data in which different sources of choice information can only be modeled by complex evidence accumulation models (Krajbich & Rangel, 2011). Future research should focus on modeling multi-choice data to gain deeper insights into decision-stage processes with respect to gender differences. Additionally, a direct comparison between DDM and LBA, as well as other variations of the DDM, could help to understand how different models may better capture individual differences in decision-making.

**Affective states associated with spatial information processing and decision-making**

A novel contribution of the present work is that the current approach incorporates affective and motivational states in understanding spatial information processing and evidence accumulation. Noisy information accumulation implies that task decisions are made under uncertainty. Such uncertainty is subject to potential influences from affective and motivational states, where potential individual and gender differences exist. The present findings highlight differential associations of affective and motivational states with information processing and decision-making strategies.

Importantly, state anxiety, confidence, and motivation, and their associations with drift rates and decision thresholds were examined. Although well-known theories, such as Attentional Control Theory (ACT) (Eysenck et al., 2007), are well-suited to explain the relation between anxiety and information processing, there is a lack of empirical evidence supporting this relation. Thus, the present work provides evidence for the association between processing efficiency (indexed by drift rates) and state anxiety on mental rotation tasks. Indeed, preliminary work examining whether anxiety from previous trials impairs drift rates on subsequent trials reveals a negative relation (Liu & Lourenco, VSS 2022), suggesting that state anxiety, either as an anticipatory response to uncertainty, or a meta-cognitive monitoring of decision uncertainty, may be associated with lower processing efficiency, consistent with the predictions of ACT. Specifically, it is likely that anxiety reduces processing efficiency via reduced working memory resources. For example, a link between working memory demands and reduced drift rates was found in children with ADHD (Kofler et al., 2020). However, more research is needed to examine how anxiety affects working memory via DDM.

Regarding confidence, most existing theoretical models of confidence have focused on decision confidence, which is typically modeled by DDM. There is agreement that confidence reflects the quality and the quantity of evidence, meaning that the stronger the evidence, the higher the confidence (Yeung & Summerfield, 2012). Importantly, confidence serves an important role in guiding future behaviors to make optimal decisions. The findings that decision confidence is associated with faster drift rates and larger decision thresholds are in line with current theories. Additionally, it is worth noting that decision confidence has been examined under the circumstances that participants had to monitor their errors post-decision. It has been suggested that post-decision processing is crucial in the decision-stage processes (Desender et al., 2019; Petrusic & Baranski, 2003; Rabbitt, 1966). Consistent with the importance of post-decision processes, preliminary work provided evidence that decision confidence may associate with short-term increases in both drift rates and decision thresholds from one trial to the next (Liu & Lourenco, VSS 2022). Thus, the role of confidence in guiding future information processing and decision-making may provide valuable insights into how participants dynamically optimize their decision strategies.

Importantly, the present work examined how affective states interacted with motivational states (Chapter 4). The relationship between motivation and affective states is generally understudied (Gable & Dreisbach, 2021). This is particularly true in the spatial domain. An important highlight from Chapter 4 is the complex interplay of motivational states, gender, and spatial mechanisms in influencing processing efficiency and evidence accumulation. The evidence thus far seems to converge with other studies showing the benefits of approach motivation and positive affect. However, their roles in attention, working memory, and executive function in relation to spatial tasks warrant further examination. For example, whether approach or avoidance motivation elicits a broadening or narrowing of attention on mental rotation tasks remains unclear. And there are questions about the mechanisms underlying attentional control and effort allocation under approach/avoidance motivation.

Current theoretical models in affective decision-making have raised concerns about the immaturity of the field, citing a lack of competing theories and many unexplored domains (Lerner et al., 2015). Although a coherent framework of affective theories in the spatial domain remains to be developed, the current dissertation calls attention to the role of affective and motivational states on spatial information processing and decision making. In addition, their interactions with gender may raise awareness for the importance of understanding how these states influence gender differences on mental rotation tasks (see subsequent section).

## Implications for gender differences on mental rotation tasks

The present findings pointed to gender differences in affective states, with women generally showing greater anxiety and lower confidence than men (Chapter 3). Importantly, gender interacted with motivational states, such that gender differences in anxiety and confidence were more pronounced in avoidance than approach motivation (Experiment 1; Chapter 4). Additionally, gender interacted with the relations between affective states and model parameters (drift rates and decision thresholds). In particular, confidence partially accounted for gender differences in drift rate and decision thresholds among participants with low motivation.

The possibility that affective variables (either state or trait) may account for gender differences in mental rotation performance aligns with various behavioral studies (Alvarez-Vargas et al., 2020; Arrighi & Hausmann, 2022; Estes & Felker, 2012). Yet, the present work provides novel evidence highlighting how affective states associate with processing efficiency and decision-making in men and women. It is important to note that affective states also interact with motivational states. For example, whereas no gender differences in confidence were observed under approach motivation, women exhibited lower confidence than men under avoidance motivation (Chapter 4). Thus, a better understanding of motivational states can shed light on gender differences in affective states.

In the same vein, an important question is where gender differences in anxiety, confidence, and motivation originate. One possibility is that stereotype threat and socio-cultural influences amplify gender differences in affective states (Levine et al., 2016; Lourenco & Liu, 2023). In addition, affective states might develop through spatial experiences. Our developmental research on children's mental rotation suggests that the magnitude of gender differences in drift rates and decision thresholds can be influenced by order of the trial difficulty (Liu & Lourenco, 2023). In this study, girls show faster drift rates on hard trials when easy trials are presented first than when hard trials are presented first. Easy trials appear to have enhanced positive affect, facilitating processing efficiency. Future work is needed to examine the development of affective states towards spatial tasks across genders.

Together, the present findings emphasize the importance of considering both affect and motivational variables when exploring gender differences. Research has shown that mental rotation performance is a strong predictor of success in STEM disciplines (Wai et al., 2009). As such, much of the existing research has largely emphasized the role of spatial training in reducing gender differences in spatial tasks (Uttal et al., 2013). Notably, training studies of spatial cognition have largely neglected the effects of affective and motivational roles on training effectiveness. Thus, the present work has important practical implications: implementing affective interventions may boost spatial training effectiveness and potentially alter baseline gender differences.

## Conclusion

There has long been interest in understanding the nature and origins of gender differences on mental rotation tasks occur. The field has focused primarily on either task-related processes or influences from socio-cultural factors. Using computational modeling from the decision sciences and borrowing theories and studies from the affective sciences, the present dissertation provides a bridge between these two areas, demonstrating that distinct stages of processing on mental rotation tasks may be differentially impacted by affective and motivational states across genders. Beyond contributing to the spatial cognition literature, this work also has highlighted the implications for gender differences in the affective domain. Our research recommends additional consideration of affective and motivational states to reduce gender differences on mental rotation tasks.

## References


Aarts, E., van Holstein, M., & Cools, R. (2011). Striatal Dopamine and the Interface between Motivation and Cognition. *Frontiers in Psychology*, *2*. https://www.frontiersin.org/articles/10.3389/fpsyg.2011.00163

Adam, J. J. (1999). Gender differences in choice reaction time: Evidence for differential strategies. *Ergonomics*, *42*(2), 327–335. https://doi.org/10.1080/001401399185685

Alvarez-Vargas, D., Abad, C., & Pruden, S. M. (2020). Spatial anxiety mediates the sex difference in adult mental rotation test performance. *Cognitive Research: Principles and Implications*, *5*(1), 31. https://doi.org/10.1186/s41235-020-00231-8

Arrighi, L., & Hausmann, M. (2022). Spatial anxiety and self-confidence mediate sex/gender differences in mental rotation. *Learning & Memory*, *29*(9), 312–320. https://doi.org/10.1101/lm.053596.122

Band, G. P. H., & Miller, J. (1997). Mental rotation interferes with response preparation. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(2), 319–338. https://doi.org/10.1037/0096-1523.23.2.319

Bauer, R., Jost, L., & Jansen, P. (2021). The effect of mindfulness and stereotype threat in mental rotation: A pupillometry study. *Journal of Cognitive Psychology*, *33*(8), 861–876. https://doi.org/10.1080/20445911.2021.1967366

Berridge, K. C., & Robinson, T. E. (2003). Parsing reward. *Trends in Neurosciences*, *26*(9), 507–513. https://doi.org/10.1016/S0166-2236(03)00233-9

Bogacz, R., Wagenmakers, E.-J., Forstmann, B. U., & Nieuwenhuis, S. (2010). The neural basis of the speed–accuracy tradeoff. *Trends in Neurosciences*, *33*(1), 10–16. https://doi.org/10.1016/j.tins.2009.09.002

Boone, A. P., & Hegarty, M. (2017). Sex differences in mental rotation tasks: Not just in the mental rotation process! *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(7), 1005–1019. https://doi.org/10.1037/xlm0000370

Borst, G., & Kosslyn, S. M. (2010). Individual Differences in Spatial Mental Imagery. *Quarterly Journal of Experimental Psychology*, *63*(10), 2031–2050. https://doi.org/10.1080/17470211003802459

Borst, G., Standing, G., & Kosslyn, S. M. (2012). Fear and anxiety modulate mental rotation. *Journal of Cognitive Psychology*, *24*(6), 665–671. https://doi.org/10.1080/20445911.2012.679924

Calcott, R. D., & Berkman, E. T. (2015). Neural Correlates of Attentional Flexibility during Approach and Avoidance Motivation. *PLOS ONE*, *10*(5), e0127203. https://doi.org/10.1371/journal.pone.0127203

Carver, C. S., & Harmon-Jones, E. (2009). Anger is an approach-related affect: Evidence and implications. *Psychological Bulletin*, *135*(2), 183–204. https://doi.org/10.1037/a0013965

Chiew, K. S., & Braver, T. S. (2014). Dissociable influences of reward motivation and positive emotion on cognitive control. *Cognitive, Affective, & Behavioral Neuroscience*, *14*(2), 509–529. https://doi.org/10.3758/s13415-014-0280-0

Choe, K. W., Jenifer, J. B., Rozek, C. S., Berman, M. G., & Beilock, S. L. (2019). Calculated avoidance: Math anxiety predicts math avoidance in effort-based decision-making. *Science Advances*, *5*(11), eaay1062. https://doi.org/10.1126/sciadv.aay1062

Cohen, M. S., Kosslyn, S. M., Breiter, H. C., DiGirolamo, G. J., Thompson, W. L., Anderson, A. K., Bookheimer, S. Y., Rosen, B. R., & Belliveau, J. W. (1996). Changes in cortical activity during mental rotation A mapping study using functional MRI. *Brain*, *119*(1), 89–100. https://doi.org/10.1093/brain/119.1.89

Coluccia, E., & Louse, G. (2004). Gender differences in spatial orientation: A review. *Journal of Environmental Psychology*, *24*(3), 329–340. https://doi.org/10.1016/j.jenvp.2004.08.006

Cooke-Simpson, A., & Voyer, D. (2007). Confidence and gender differences on the Mental Rotations Test. *Learning and Individual Differences*, *17*(2), 181–186. https://doi.org/10.1016/j.lindif.2007.03.009

Coombes, S. A., Higgins, T., Gamble, K. M., Cauraugh, J. H., & Janelle, C. M. (2009). Attentional control theory: Anxiety, emotion, and motor planning. *Journal of Anxiety Disorders*, *23*(8), 1072–1079. https://doi.org/10.1016/j.janxdis.2009.07.009

Corballis, M. C., & Manalo, R. (1993). Effect of spatial attention on mental rotation. *Neuropsychologia*, *31*(2), 199–205. https://doi.org/10.1016/0028-3932(93)90047-4

Corr, P. J., & McNaughton, N. (2012). Neuroscience and approach/avoidance personality traits: A two stage (valuation–motivation) approach. *Neuroscience & Biobehavioral Reviews*, *36*(10), 2339–2354. https://doi.org/10.1016/j.neubiorev.2012.09.013

Cross, C. P., Brown, G. R., Morgan, T. J. H., & Laland, K. N. (2017). Sex differences in confidence influence patterns of conformity. *British Journal of Psychology*, *108*(4), 655–667. https://doi.org/10.1111/bjop.12232
Dambacher, M. (2011). Monetary incentives in speeded perceptual decision: Effects of penalizing errors versus slow responses. *Frontiers in Psychology*, *2*. https://doi.org/10.3389/fpsyg.2011.00248
Dambacher, M., & Hübner, R. (2015). Time pressure affects the efficiency of perceptual processing in decisions under conflict. *Psychological Research*, *79*(1), 83–94. https://doi.org/10.1007/s00426-014-0542-z
Debelak, R., Gittler, G., & Arendasy, M. (2014). On gender differences in mental rotation processing speed. *Learning and Individual Differences*, *29*, 8–17. https://doi.org/10.1016/j.lindif.2013.10.003
Desender, K., Boldt, A., Verguts, T., & Donner, T. H. (2019). Confidence predicts speed-accuracy tradeoff for subsequent decisions. *eLife*, *8*, e43499. https://doi.org/10.7554/eLife.43499
Dix, A., & Li, S.-C. (2020). Incentive motivation improves numerosity discrimination: Insights from pupillometry combined with drift-diffusion modelling. *Scientific Reports*, *10*(1), 2608. https://doi.org/10.1038/s41598-020-59415-3
Estes, Z., & Felker, S. (2012). Confidence Mediates the Sex Difference in Mental Rotation Performance. *Archives of Sexual Behavior*, *41*(3), 557–570. https://doi.org/10.1007/s10508-011-9875-5
Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion*, *7*(2), 336–353. https://doi.org/10.1037/1528-3542.7.2.336
Forstmann, B. U., Ratcliff, R., & Wagenmakers, E.-J. (2016). Sequential Sampling Models in Cognitive Neuroscience: Advantages, Applications, and Extensions. *Annual Review of Psychology*, *67*(1), 641–666. https://doi.org/10.1146/annurev-psych-122414-033645
Fredrickson, B. L. (2013). Positive Emotions Broaden and Build. In *Advances in Experimental Social Psychology* (Vol. 47, pp. 1–53). Elsevier. https://doi.org/10.1016/B978-0-12-407236-7.00001-2
Friedman, R. S., & Förster, J. (2001). The effects of promotion and prevention cues on creativity. *Journal of Personality and Social Psychology*, *81*(6), 1001–1013. https://doi.org/10.1037/0022-3514.81.6.1001
Friedman, R. S., & Förster, J. (2002). The Influence of Approach and Avoidance Motor Actions on Creative Cognition. *Journal of Experimental Social Psychology*, *38*(1), 41–55. https://doi.org/10.1006/jesp.2001.1488
Fröber, K., & Dreisbach, G. (2014). The differential influences of positive affect, random reward, and performance-contingent reward on cognitive control. *Cognitive, Affective, & Behavioral Neuroscience*, *14*(2), 530–547. https://doi.org/10.3758/s13415-014-0259-x
Gable, P. A., & Dreisbach, G. (2021). Approach motivation and positive affect. *Current Opinion in Behavioral Sciences*, *39*, 203–208. https://doi.org/10.1016/j.cobeha.2021.03.030
Ganis, G., & Kievit, R. (2015). A New Set of Three-Dimensional Shapes for Investigating Mental Rotation Processes: Validation Data and Stimulus Set. *Journal of Open Psychology Data*, *3*. https://doi.org/10.5334/jopd.ai
Gardony, A. L., Eddy, M. D., Brunyé, T. T., & Taylor, H. A. (2017). Cognitive strategies in the mental rotation task revealed by EEG spectral power. *Brain and Cognition*, *118*, 1–18. https://doi.org/10.1016/j.bandc.2017.07.003
Gasper, K., & Clore, G. L. (2002). Attending to the Big Picture: Mood and Global Versus Local Processing of Visual Information. *Psychological Science*, *13*(1), 34–40. https://doi.org/10.1111/1467-9280.00406
Geiser, C., Lehmann, W., & Eid, M. (2006). Separating "Rotators" From "Nonrotators" in the Mental Rotations Test: A Multigroup Latent Class Analysis. *Multivariate Behavioral Research*, *41*(3), 261–293. https://doi.org/10.1207/s15327906mbr4103_2
Gelman, A., & Rubin, D. B. (1992). Inference from Iterative Simulation Using Multiple Sequences. *Statistical Science*, *7*(4). https://doi.org/10.1214/ss/1177011136
Glück, J., & Fabrizii, C. (2010). Gender Differences in the Mental Rotations Test Are Partly Explained by Response Format. *Journal of Individual Differences*, *31*(2), 106–109. https://doi.org/10.1027/1614-0001/a000019
Goldstein, D., Haldane, D., & Mitchell, C. (1990). Sex differences in visual-spatial ability: The role of performance factors. *Memory & Cognition*, *18*(5), 546–550. https://doi.org/10.3758/BF03198487
Hamm, J. (2004). One good turn deserves another: An event-related brain potential study of rotated mirror–normal letter discriminations. *Neuropsychologia*, *42*(6), 810–820. https://doi.org/10.1016/j.neuropsychologia.2003.11.009

Hamrick, J. B. (2019). Analogues of mental simulation and imagination in deep learning. *Current Opinion in Behavioral Sciences*, *29*, 8–16. https://doi.org/10.1016/j.cobeha.2018.12.011
Hartley, C. A., & Phelps, E. A. (2012). Anxiety and Decision-Making. *Biological Psychiatry*, *72*(2), 113–118. https://doi.org/10.1016/j.biopsych.2011.12.027
Hauser, T. U., Moutoussis, M., NSPN Consortium, Dayan, P., & Dolan, R. J. (2017). Increased decision thresholds trigger extended information gathering across the compulsivity spectrum. *Translational Psychiatry*, *7*(12), 1296. https://doi.org/10.1038/s41398-017-0040-3
Heathcote, A., & Matzke, D. (2022). Winner Takes All! What Are Race Models, and Why and How Should Psychologists Use Them? *Current Directions in Psychological Science*, *31*(5), 383–394. https://doi.org/10.1177/09637214221095852
Heil, M., & Jansen-Osmann, P. (2008). Sex Differences in Mental Rotation with Polygons of Different Complexity: Do Men Utilize Holistic Processes whereas Women Prefer Piecemeal Ones? *Quarterly Journal of Experimental Psychology*, *61*(5), 683–689. https://doi.org/10.1080/17470210701822967
Heil, M., & Rolke, B. (2002). Toward a chronopsychophysiology of mental rotation. *Psychophysiology*, *39*(4), 414–422. https://doi.org/10.1111/1469-8986.3940414
Herz, D. M., Little, S., Pedrosa, D. J., Tinkhauser, G., Cheeran, B., Foltynie, T., Bogacz, R., & Brown, P. (2018). Mechanisms Underlying Decision-Making as Revealed by Deep-Brain Stimulation in Patients with Parkinson's Disease. *Current Biology*, *28*(8), 1169-1178.e6. https://doi.org/10.1016/j.cub.2018.02.057
Hirnstein, M., Bayer, U., & Hausmann, M. (2009). Sex-specific response strategies in mental rotation. *Learning and Individual Differences*, *19*(2), 225–228. https://doi.org/10.1016/j.lindif.2008.11.006
Ho, T., Brown, S., van Maanen, L., Forstmann, B. U., Wagenmakers, E.-J., & Serences, J. T. (2012). The Optimality of Sensory Processing during the Speed-Accuracy Tradeoff. *Journal of Neuroscience*, *32*(23), 7992–8003. https://doi.org/10.1523/JNEUROSCI.0340-12.2012
Hooven, C. (2004). The relationship of male testosterone to components of mental rotation. *Neuropsychologia*, *42*(6), 782–790. https://doi.org/10.1016/j.neuropsychologia.2003.11.012
Hübner, R., & Schlösser, J. (2010). Monetary reward increases attentional effort in the flanker task. *Psychonomic Bulletin & Review*, *17*(6), 821–826. https://doi.org/10.3758/PBR.17.6.821
Hyun, J.-S., & Luck, S. J. (2007). Visual working memory as the substrate for mental rotation. *Psychonomic Bulletin & Review*, *14*(1), 154–158. https://doi.org/10.3758/BF03194043
Ilan, A. B., & Miller, J. (1994). A violation of pure insertion: Mental rotation and choice reaction time. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(3), 520–536. https://doi.org/10.1037/0096-1523.20.3.520
Ito, R., & Lee, A. C. H. (2016). The role of the hippocampus in approach-avoidance conflict decision-making: Evidence from rodent and human studies. *Behavioural Brain Research*, *313*, 345–357. https://doi.org/10.1016/j.bbr.2016.07.039
Jansen, P., & Kaltner, S. (2014). Object-based and egocentric mental rotation performance in older adults: The importance of gender differences and motor ability. *Aging, Neuropsychology, and Cognition*, *21*(3), 296–316. https://doi.org/10.1080/13825585.2013.805725
Jansen, P., Kaltner, S., & Memmert, D. (2017). Approaching behavior reduces gender differences in the mental rotation performance. *Psychological Research*, *81*(6), 1192–1200. https://doi.org/10.1007/s00426-016-0817-7
Jansen-Osmann, P., & Heil, M. (2007). Suitable stimuli to obtain (no) gender differences in the speed of cognitive processes involved in mental rotation. *Brain and Cognition*, *64*(3), 217–227. https://doi.org/10.1016/j.bandc.2007.03.002
Just, M. A., & Carpenter, P. A. (1976). Eye fixations and cognitive processes. *Cognitive Psychology*, *8*(4), 441–480. https://doi.org/10.1016/0010-0285(76)90015-3
Kail, R., Carter, P., & Pellegrino, J. (1979). The locus of sex differences in spatial ability. *Perception & Psychophysics*, *26*(3), 182–186. https://doi.org/10.3758/BF03199867
Kerkman, D. D., Wise, J. C., & Harwood, E. A. (2000). Impossible "mental rotation" problems. *Learning and Individual Differences*, *12*(3), 253–269. https://doi.org/10.1016/S1041-6080(01)00039-5
Koch, S., Holland, R. W., & Van Knippenberg, A. (2008). Regulating cognitive control through approach-avoidance motor actions. *Cognition*, *109*(1), 133–142. https://doi.org/10.1016/j.cognition.2008.07.014

Kofler, M. J., Soto, E. F., Fosco, W. D., Irwin, L. N., Wells, E. L., & Sarver, D. E. (2020). Working memory and information processing in ADHD: Evidence for directionality of effects. *Neuropsychology*, *34*(2), 127–143. https://doi.org/10.1037/neu0000598
Krajbich, I., & Rangel, A. (2011). Multialternative drift-diffusion model predicts the relationship between visual fixations and choice in value-based decisions. *Proceedings of the National Academy of Sciences*, *108*(33), 13852–13857. https://doi.org/10.1073/pnas.1101328108
Larsen, A. (2014). Deconstructing mental rotation. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(3), 1072–1091. https://doi.org/10.1037/a0035648
Leng, X., Yee, D., Ritz, H., & Shenhav, A. (2021). Dissociable influences of reward and punishment on adaptive cognitive control. *PLOS Computational Biology*, *17*(12), e1009737. https://doi.org/10.1371/journal.pcbi.1009737
Lerner, J. S., Li, Y., Valdesolo, P., & Kassam, K. S. (2015). Emotion and Decision Making. *Annual Review of Psychology*, *66*(1), 799–823. https://doi.org/10.1146/annurev-psych-010213-115043
Levine, S. C., Foley, A., Lourenco, S., Ehrlich, S., & Ratliff, K. (2016). Sex differences in spatial cognition: Advancing the conversation. *WIREs Cognitive Science*, *7*(2), 127–155. https://doi.org/10.1002/wcs.1380
Levine, S. C., Vasilyeva, M., Lourenco, S. F., Newcombe, N. S., & Huttenlocher, J. (2005). Socioeconomic Status Modifies the Sex Difference in Spatial Skill. *Psychological Science*, *16*(11), 841–845. https://doi.org/10.1111/j.1467-9280.2005.01623.x
Lippa, R. A., Collaer, M. L., & Peters, M. (2010). Sex Differences in Mental Rotation and Line Angle Judgments Are Positively Associated with Gender Equality and Economic Development Across 53 Nations. *Archives of Sexual Behavior*, *39*(4), 990–997. https://doi.org/10.1007/s10508-008-9460-8
Liu, L., Wu, J., Geng, H., Liu, C., Luo, Y., Luo, J., & Qin, S. (2022). Long-term stress and trait anxiety affect brain network balance in dynamic cognitive computations. *Cerebral Cortex*, *32*(14), 2957–2971. https://doi.org/10.1093/cercor/bhab393
Liu, Y., & Lourenco, S. F. (2022). Affective Factors Affect Visuospatial Decision-making: A Drift Diffusion Modeling Approach. *Proceedings of the Annual Meeting of the Cognitive Science Society*, 44. Retrieved from https://escholarship.org/uc/item/9kd457qg
Liu, Y., & Lourenco, S. F. (2022b). Drift diffusion modeling informs how affective factors affect visuospatial decision making. *Journal of Vision*, *22*(14), 3394. https://doi.org/10.1167/jov.22.14.3394
Liu, Y., & Lourenco, S. F. (2023). *Trial history influences the malleability of gender differences in children's mental rotation performance*. *Proceedings of the Annual Meeting of the Cognitive Science Society*, 45. Retrieved from https://escholarship.org/uc/item/65j3s6g6
Lochbaum, M., & Gottardy, J. (2015). A meta-analytic review of the approach-avoidance achievement goals and performance relationships in the sport psychology literature. *Journal of Sport and Health Science*, *4*(2), 164–173. https://doi.org/10.1016/j.jshs.2013.12.004
Lourenco, S. F., & Liu, Y. (2023). The Impacts of Anxiety and Motivation on Spatial Performance: Implications for Gender Differences in Mental Rotation and Navigation. *Current Directions in Psychological Science*, *32*(3), 187–196. https://doi.org/10.1177/09637214231153072
Lyons, I. M., Ramirez, G., Maloney, E. A., Rendina, D. N., Levine, S. C., & Beilock, S. L. (2018). Spatial Anxiety: A Novel Questionnaire With Subscales for Measuring Three Aspects of Spatial Anxiety. *Journal of Numerical Cognition*, *4*(3), 526–553. https://doi.org/10.5964/jnc.v4i3.154
Martinaud, O., Mirlink, N., Bioux, S., Bliaux, E., Champmartin, C., Pouliquen, D., Cruypeninck, Y., Hannequin, D., & Gérardin, E. (2016). Mirrored and rotated stimuli are not the same: A neuropsychological and lesion mapping study. *Cortex*, *78*, 100–114. https://doi.org/10.1016/j.cortex.2016.03.002
Menéndez Granda, M., Iannotti, G. R., Darqué, A., & Ptak, R. (2022). Does mental rotation emulate motor processes? An electrophysiological study of objects and body parts. *Frontiers in Human Neuroscience*, *16*, 983137. https://doi.org/10.3389/fnhum.2022.983137
Meyniel, F., Sigman, M., & Mainen, Z. F. (2015). Confidence as Bayesian Probability: From Neural Origins to Behavior. *Neuron*, *88*(1), 78–92. https://doi.org/10.1016/j.neuron.2015.09.039
Miron-Spektor, E., Efrat-Treister, D., Rafaeli, A., & Schwarz-Cohen, O. (2011). Others' anger makes people work harder not smarter: The effect of observing anger and sarcasm on creative and analytic thinking. *Journal of Applied Psychology*, *96*(5), 1065–1075. https://doi.org/10.1037/a0023593

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General*, *130*(4), 621–640. https://doi.org/10.1037/0096-3445.130.4.621
Moè, A. (2016). Teaching motivation and strategies to improve mental rotation abilities. *Intelligence*, *59*, 16–23. https://doi.org/10.1016/j.intell.2016.10.004
Moè, A., & Pazzaglia, F. (2010). Beyond genetics in Mental Rotation Test performance: The power of effort attribution. *Learning and Individual Differences*, *20*(5), 464–468. https://doi.org/10.1016/j.lindif.2010.03.004
Mohanty, A., Jin, F., & Sussman, T. (2023). What Do We Know About Threat-Related Perceptual Decision Making? *Current Directions in Psychological Science*, *32*(1), 18–25. https://doi.org/10.1177/09637214221129795
Murty, V. P., LaBar, K. S., Hamilton, D. A., & Adcock, R. A. (2011). Is all motivation good for learning? Dissociable influences of approach and avoidance motivation in declarative memory. *Learning & Memory*, *18*(11), 712–717. https://doi.org/10.1101/lm.023549.111
Nazareth, A., Herrera, A., & Pruden, S. M. (2013). Explaining sex differences in mental rotation: Role of spatial activity experience. *Cognitive Processing*, *14*(2), 201–204. https://doi.org/10.1007/s10339-013-0542-8
Osth, A. F., Bora, B., Dennis, S., & Heathcote, A. (2017). Diffusion vs. linear ballistic accumulation: Different models, different conclusions about the slope of the zROC in recognition memory. *Journal of Memory and Language*, *96*, 36–61. https://doi.org/10.1016/j.jml.2017.04.003
Paschke, K., Jordan, K., Wüstenberg, T., Baudewig, J., & Leo Müller, J. (2012). Mirrored or identical—Is the role of visual perception underestimated in the mental rotation process of 3D-objects?: A combined fMRI-eye tracking-study. *Neuropsychologia*, *50*(8), 1844–1851. https://doi.org/10.1016/j.neuropsychologia.2012.04.010
Paulus, M. P., & Yu, A. J. (2012). Emotion and decision-making: Affect-driven belief systems in anxiety and depression. *Trends in Cognitive Sciences*, *16*(9), 476–483. https://doi.org/10.1016/j.tics.2012.07.009
Pazzaglia, F., & Moè, A. (2013). Cognitive styles and mental rotation ability in map learning. *Cognitive Processing*, *14*(4), 391–399. https://doi.org/10.1007/s10339-013-0572-2
Peirce, J. W. (2008). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics*, *2*. https://doi.org/10.3389/neuro.11.010.2008
Pessoa, L. (2009). How do emotion and motivation direct executive control? *Trends in Cognitive Sciences*, *13*(4), 160–166. https://doi.org/10.1016/j.tics.2009.01.006
Peters, M. (2005). Sex differences and the factor of time in solving Vandenberg and Kuse mental rotation problems. *Brain and Cognition*, *57*(2), 176–184. https://doi.org/10.1016/j.bandc.2004.08.052
Peters, M., Lehmann, W., Takahira, S., Takeuchi, Y., & Jordan, K. (2006). Mental Rotation Test Performance in Four Cross-Cultural Samples (N = 3367): Overall Sex Differences and the Role of Academic Program in Performance. *Cortex*, *42*(7), 1005–1014. https://doi.org/10.1016/S0010-9452(08)70206-5
Petrusic, W. M., & Baranski, J. V. (2003). Judging confidence influences decision processing in comparative judgments. *Psychonomic Bulletin & Review*, *10*(1), 177–183. https://doi.org/10.3758/BF03196482
Pieters, R., & Warlop, L. (1999). Visual attention during brand choice: The impact of time pressure and task motivation. *International Journal of Research in Marketing*, *16*(1), 1–16. https://doi.org/10.1016/S0167-8116(98)00022-6
Prinzel, L. J., & Freeman, F. G. (1995). Sex Differences in Visuo-Spatial Ability: Task Difficulty, Speed-Accuracy Tradeoff, and Other Performance Factors. *Canadian Journal of Experimental Psychology / Revue Canadienne de Psychologie Expérimentale*, *49*(4), 530–539. https://doi.org/10.1037/1196-1961.49.4.530
Provost, A., & Heathcote, A. (2015). Titrating decision processes in the mental rotation task. *Psychological Review*, *122*(4), 735–754. https://doi.org/10.1037/a0039706
Rabbitt, P. M. (1966). Errors and error correction in choice-response tasks. *Journal of Experimental Psychology*, *71*(2), 264–272. https://doi.org/10.1037/h0022853
Rae, B., Heathcote, A., Donkin, C., Averell, L., & Brown, S. (2014). The hare and the tortoise: Emphasizing speed can change the evidence used to make decisions. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(5), 1226–1243. https://doi.org/10.1037/a0036801

Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L. (2012). Spatial Anxiety Relates to Spatial Abilities as a Function of Working Memory in Children. *Quarterly Journal of Experimental Psychology*, *65*(3), 474–487. https://doi.org/10.1080/17470218.2011.616214
Ratcliff, R. (2014). Measuring psychometric functions with the diffusion model. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(2), 870–888. https://doi.org/10.1037/a0034954
Ratcliff, R., & Childers, R. (2015). Individual differences and fitting methods for the two-choice diffusion model of decision making. *Decision*, *2*(4), 237–279. https://doi.org/10.1037/dec0000030
Ratcliff, R., & McKoon, G. (2008). The Diffusion Decision Model: Theory and Data for Two-Choice Decision Tasks. *Neural Computation*, *20*(4), 873–922. https://doi.org/10.1162/neco.2008.12-06-420
Ratcliff, R., & Rouder, J. N. (1998). Modeling Response Times for Two-Choice Decisions. *Psychological Science*, *9*(5), 347–356. https://doi.org/10.1111/1467-9280.00067
Ratcliff, R., & Smith, P. L. (2004). A Comparison of Sequential Sampling Models for Two-Choice Reaction Time. *Psychological Review*, *111*(2), 333–367. https://doi.org/10.1037/0033-295X.111.2.333
Ratcliff, R., Thapar, A., & Mckoon, G. (2003). A diffusion model analysis of the effects of aging on brightness discrimination. *Perception & Psychophysics*, *65*(4), 523–535. https://doi.org/10.3758/BF03194580
Roberts, I. D., & Hutcherson, C. A. (2019). Affect and Decision Making: Insights and Predictions from Computational Models. *Trends in Cognitive Sciences*, *23*(7), 602–614. https://doi.org/10.1016/j.tics.2019.04.005
Roskes, M., Elliot, A. J., & De Dreu, C. K. W. (2014). Why Is Avoidance Motivation Problematic, and What Can Be Done About It? *Current Directions in Psychological Science*, *23*(2), 133–138. https://doi.org/10.1177/0963721414524224
Rossi, J. S., & Collyer, C. E. (1986). Is there a threshold for mental rotation? *Bulletin of the Psychonomic Society*, *24*(1), 1–3. https://doi.org/10.3758/BF03330486
Russell, J. A. (2003). Core affect and the psychological construction of emotion. *Psychological Review*, *110*(1), 145–172. https://doi.org/10.1037/0033-295X.110.1.145
Searle, J. A., & Hamm, J. P. (2017). Mental rotation: An examination of assumptions. *WIREs Cognitive Science*, *8*(6). https://doi.org/10.1002/wcs.1443
Shackman, A. J., Sarinopoulos, I., Maxwell, J. S., Pizzagalli, D. A., Lavric, A., & Davidson, R. J. (2006). Anxiety selectively disrupts visuospatial working memory. *Emotion*, *6*(1), 40–61. https://doi.org/10.1037/1528-3542.6.1.40
Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017). Toward a Rational and Mechanistic Account of Mental Effort. *Annual Review of Neuroscience*, *40*(1), 99–124. https://doi.org/10.1146/annurev-neuro-072116-031526
Shepard, R. N., & Metzler, J. (1971). Mental Rotation of Three-Dimensional Objects. *Science*, *171*(3972), 701–703. https://www.jstor.org/stable/1731476
Simon, H. A. (1979). Information Processing Models of Cognition. *Annual Review of Psychology*, *30*(1), 363–396. https://doi.org/10.1146/annurev.ps.30.020179.002051
Sokolowski, H. M., Hawes, Z., & Lyons, I. M. (2019). What explains sex differences in math anxiety? A closer look at the role of spatial processing. *Cognition*, *182*, 193–212. https://doi.org/10.1016/j.cognition.2018.10.005
Spielberger, C. D. (2012). *State-Trait Anxiety Inventory for Adults* [dataset]. https://doi.org/10.1037/t06496-000
Spliethoff, L., Li, S.-C., & Dix, A. (2022). Incentive motivation improves numerosity discrimination in children and adolescents. *Scientific Reports*, *12*(1), 10038. https://doi.org/10.1038/s41598-022-14198-7
Starcke, K., & Brand, M. (2012). Decision making under stress: A selective review. *Neuroscience & Biobehavioral Reviews*, *36*(4), 1228–1248. https://doi.org/10.1016/j.neubiorev.2012.02.003
Starns, J. J., Ratcliff, R., & White, C. N. (2012). Diffusion model drift rates can be influenced by decision processes: An analysis of the strength-based mirror effect. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(5), 1137–1151. https://doi.org/10.1037/a0028151
Swanson, J. M., & Briggs, G. E. (1969). Information processing as a function of speed versus accuracy. *Journal of Experimental Psychology*, *81*(2), 223–229. https://doi.org/10.1037/h0027774
Teboul, A., Klosek, C., Montiny, C., & Gernigon, C. (2019). Development and Validation of the Approach-Avoidance System Questionnaire (AASQ). *Frontiers in Psychology*, *10*, 2531. https://doi.org/10.3389/fpsyg.2019.02531

Threadgill, A. H., & Gable, P. A. (2016). Approach-motivated pregoal states enhance the reward positivity: Approach motivation enhances reward positivity. *Psychophysiology*, *53*(5), 733–738. https://doi.org/10.1111/psyp.12611

Titze, C., Heil, M., & Jansen, P. (2008). Gender Differences in the Mental Rotations Test (MRT) Are Not Due to Task Complexity. *Journal of Individual Differences*, *29*(3), 130–133. https://doi.org/10.1027/1614-0001.29.3.130

Toth, A. J., & Campbell, M. J. (2019). Investigating sex differences, cognitive effort, strategy, and performance on a computerised version of the mental rotations test via eye tracking. *Scientific Reports*, *9*(1), 19430. https://doi.org/10.1038/s41598-019-56041-6

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402. https://doi.org/10.1037/a0028446

Vandenberg, S. G., & Kuse, A. R. (1978). Mental Rotations, a Group Test of Three-Dimensional Spatial Visualization. *Perceptual and Motor Skills*, *47*(2), 599–604. https://doi.org/10.2466/pms.1978.47.2.599

Voss, A., Rothermund, K., & Voss, J. (2004). Interpreting the parameters of the diffusion model: An empirical validation. *Memory & Cognition*, *32*(7), 1206–1220. https://doi.org/10.3758/BF03196893

Voyer, D. (2011). Time limits and gender differences on paper-and-pencil tests of mental rotation: A meta-analysis. *Psychonomic Bulletin & Review*, *18*(2), 267–277. https://doi.org/10.3758/s13423-010-0042-0

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, *117*(2), 250–270. https://doi.org/10.1037/0033-2909.117.2.250

Wagenmakers, E.-J., Ratcliff, R., Gomez, P., & McKoon, G. (2008). A diffusion model account of criterion shifts in the lexical decision task. *Journal of Memory and Language*, *58*(1), 140–159. https://doi.org/10.1016/j.jml.2007.04.006

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*(4), 817–835. https://doi.org/10.1037/a0016127

Wang, L., & Carr, M. (2014). Working Memory and Strategy Use Contribute to Gender Differences in Spatial Ability. *Educational Psychologist*, *49*(4), 261–282. https://doi.org/10.1080/00461520.2014.960568

White, C. N., Ratcliff, R., & Starns, J. J. (2011). Diffusion models of the flanker task: Discrete versus gradual attentional selection. *Cognitive Psychology*, *63*(4), 210–238. https://doi.org/10.1016/j.cogpsych.2011.08.001

Wiecki, T. V., Sofer, I., & Frank, M. J. (2013). HDDM: Hierarchical Bayesian estimation of the Drift-Diffusion Model in Python. *Frontiers in Neuroinformatics*, *7*. https://doi.org/10.3389/fninf.2013.00014

Wiedenbauer, G., Schmid, J., & Jansen-Osmann, P. (2007). Manual training of mental rotation. *European Journal of Cognitive Psychology*, *19*(1), 17–36. https://doi.org/10.1080/09541440600709906

Wong, A. L., Goldsmith, J., Forrence, A. D., Haith, A. M., & Krakauer, J. W. (2017). Reaction times can reflect habits rather than computations. *eLife*, *6*, e28075. https://doi.org/10.7554/eLife.28075

Wraga, M., Duncan, L., Jacobs, E. C., Helt, M., & Church, J. (2006). Stereotype susceptibility narrows the gender gap in imagined self-rotation performance. *Psychonomic Bulletin & Review*, *13*(5), 813–819. https://doi.org/10.3758/BF03194002

Yee, D. M., Leng, X., Shenhav, A., & Braver, T. S. (2022). Aversive motivation and cognitive control. *Neuroscience & Biobehavioral Reviews*, *133*, 104493. https://doi.org/10.1016/j.neubiorev.2021.12.016

Yeung, N., & Summerfield, C. (2012). Metacognition in human decision-making: Confidence and error monitoring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1594), 1310–1321. https://doi.org/10.1098/rstb.2011.0416

Yu, L., Wang, X., Lyu, Y., Ding, L., Jia, J., Tong, S., & Guo, X. (2020). Electrophysiological Evidences for the Rotational Uncertainty Effect in the Hand Mental Rotation: An ERP and ERS/ERD Study. *Neuroscience*, *432*, 205–215. https://doi.org/10.1016/j.neuroscience.2020.02.040

Zacks, J. M. (2008). Neuroimaging Studies of Mental Rotation: A Meta-analysis and Review. *Journal of Cognitive Neuroscience*, *20*(1), 1–19. https://doi.org/10.1162/jocn.2008.20013

Zhang, J., & Rowe, J. B. (2014). Dissociable mechanisms of speed-accuracy tradeoff during visual perceptual learning are revealed by a hierarchical drift-diffusion model. *Frontiers in Neuroscience*, *8*. https://doi.org/10.3389/fnins.2014.00069