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Prior probabilities and representational momentum

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In many previous experiments on representational momentum (in which memory for the final location of a moving target is displaced in the direction of target motion), participants judged whether a probe presented after a target vanished was at the same location where that target vanished or at a different location. The experiments reported here manipulated the actual or expected prior probability a *same* response to such a probe would be correct. In Experiment 1, a *same* response was correct on 10%, 30%, 50%, 70%, or 90% of the trials, but observers were not instructed regarding these probabilities. In Experiment 2, a *same* response was correct on 11% of the trials, but different groups of participants were instructed that a *same* response would be correct on 10%, 30%, 50%, 70%, or 90% of the trials. Probabilities of a *same* response to different probe positions, weighted mean estimates of representational momentum, hit rates and false alarm rates, and d' and ß are reported. Representational momentum occurred in all conditions but was not influenced by actual or expected prior probability a *same* response would be correct. The data suggest representational momentum does not result from changes in sensitivity, and a distinction between performance bias and competence bias is introduced.

Keywords: Representational momentum; Displacement; Prior probabilities; Mislocalization; Signal detection theory.

Memory for the final location of a moving target is often displaced in the direction of target motion; that is, a target is remembered as having travelled slightly further than it actually travelled. This displacement has been referred

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to as *representational momentum* (Freyd & Finke, 1984; for review, see Hubbard, 2005). It is well-established that an observer's expectations regarding subsequent target behaviour (e.g., Johnston & Jones, 2006; Verfaillie & d'Ydewalle, 1991) and interactions of the target with a nontarget stimulus (e.g., Hubbard, 1994; Hubbard, Blessum, & Ruppel, 2001) can influence such displacement. However, whether an observer's expectations regarding how memory for the target would be measured can influence such displacement has not been examined. The experiments reported here examined effects on representational momentum of the actual or expected prior probability a *same* response would be correct in a judgement of whether the location of a probe was the same as or different from the final location of a previously viewed moving target. The experiments reported here (1) provide vital data regarding the suitability of a commonly used methodology in the study of displacement, (2) demonstrate a new way signal detection theory can be applied in analysis of psychometric functions, (3) consider whether representational momentum is influenced by changes in sensitivity or in bias, and (4) introduce a distinction between performance bias and competence bias.

A common methodology within the representational momentum literature for assessing displacement is to present a probe after the moving target vanished. The probe is usually the same size and shape as the target, and probe position relative to the final location of the target is varied across trials. The probe can be either slightly behind where the target vanished (i.e., shifted backward in the direction opposite to target motion), at the same location where the target vanished, or slightly beyond where the target vanished (i.e., shifted forward in the direction of target motion). Participants provide a judgement of *same* or *different* regarding whether the probe is at the same location where the target vanished or at a different location. The probabilities of a *same* response across all probe positions are used to calculate an estimate of displacement. There are usually five, seven, or nine probe positions used in an experiment, with one probe position corresponding to the final location of the target and other probe positions equally distributed between positions behind the final location of the target and positions beyond the final location of the target. Each probe position is usually equally likely across the trials of an experiment, and so the more probe positions that are used, the lower the prior probability a *same* response will be correct on any given trial (e.g., a *same* response would be correct on 1/5, 1/7, or 1/9 of the trials when five, seven, or nine different probe positions, respectively, are used).

Studies of representational momentum have typically not informed participants about nor manipulated the prior probability a *same* response would be correct, and it is not known how differences in prior probability or how mismatches between actual and expected prior probability might influence displacement. The studies within the representational momentum literature most relevant to these issues are those in which participants received feedback regarding their responses on each trial, as such feedback provides participants a way to potentially ascertain the prior probability a *same* response would be correct. Finke and Freyd (1985) presented participants with implied motion of a target, and participants judged whether a subsequently presented probe was at the same location where the target vanished. Feedback was provided during a small number of practice trials. Displacement on subsequent experimental trials did not differ between participants who received feedback on practice trials and participants who did not receive feedback, nor did displacement differ across blocks of experimental trials. Based on these results, Finke and Freyd suggested displacement is not influenced by feedback. However, Joordens, Spalek, Razmy, and van Duijn (2004) suggested exposure to feedback during a limited number of practice trials in Finke and Freyd did not provide sufficient exposure for learning from feedback to have occurred. Similarly, exposure to feedback during a limited number of practice trials might not provide sufficient exposure for participants to ascertain the prior probability a *same* response would be correct.

Taking note of Joorden et al.'s (2004) suggestion, Ruppel, Fleming, and Hubbard (2009) presented feedback regarding participants' judgements of probes over a much larger number of trials. Feedback influenced the likelihood of a *same* response (i.e., the height of the distribution of the probability of *same* responses as a function of probe position), but feedback did not influence estimates of forward displacement (i.e., the shape of the distribution of the probability of *same* responses as a function of probe position). More specifically, the presence of feedback decreased the probability of *same* responses in general, but did not influence the relatively greater likelihood of *same* responses for probes beyond the final location of the target than for probes behind the final location of the target. Seven probe positions were used, and so on any given trial, a *same* response was much less likely to be correct than was a *different* response (i.e., a *same* response was correct on only 1/7 of the trials). Ruppel et al. speculated that participants initially assumed there would be equal numbers of *same* responses and *different* responses, and so prior to receiving feedback, participants responded as if they expected equal numbers of *same* responses and *different* responses. A relatively small number of trials might have been sufficient for participants to learn that on any given trial a response of *same* was less likely to be correct than was a response of *different*, and so the probability participants would generate a *same* response on any given trial decreased.

If participants' responses in Ruppel et al. (2009) were influenced by expectations regarding the prior probability a *same* response to a subsequent probe would be correct, then manipulation of prior probability should similarly influence participants' responding. More explicitly, it could be predicted that decreases in actual prior probability or expected prior probability a *same* response would be correct should result in decreases in the likelihood of a *same* response but should not influence estimates of forward displacement. However, data in Ruppel et al. do not allow a clear examination of the effects of actual prior probability or expected prior probability, nor have other experiments within the representational momentum literature examined potential effects on participants' responses of manipulating actual prior probability or expected prior probability a response of *same* to a subsequent probe of the final location of the target would be correct. The potential importance of manipulating actual prior probability or expected prior probability on participants' responses goes well beyond addressing a speculation in Ruppel et al.; indeed, given the extensive use of probe judgement methodology within the representational momentum literature, an examination of potential effects on participants' responses of actual prior probability or expected prior probability a *same* response would be correct allows a potentially critical evaluation of a common methodology.

An examination of effects on representational momentum of actual prior probability or expected prior probability a *same* response to a subsequent probe would be correct can be considered analogous to an examination of effects on signal detection of prior probability a signal would be present. Indeed, a consistent mapping of stimulus categories and response categories in experiments on representational momentum onto stimulus categories and response categories in experiments on signal detection can be suggested. In a consideration of stimulus categories, a probe at the actual final location of the target would be analogous to the presence of a signal, and a probe at a different location would be analogous to the absence of a signal. In a consideration of response categories, a *same* response to a probe at the final location of the target would be a "hit", a *same* response to a probe not at the final location of the target would be a "false alarm", a *different* response to a probe at the final location of the target would be a "miss", and a *different* response to a probe not at the final location of the target would be a "correct rejection". Varying the prior probability a probe would be at the final location of the target (i.e., that a signal was present) and observing effects of such variation on probe judgement and on displacement would be analogous to varying the payoff matrix in a signal detection experiment and observing effects of such variation on signal detection.[1]

[1] It might be objected that probes more distant from the final position of the target were weaker in "signal strength" than were probes closer to the final position of the target, and therefore the signal strength of probes varied across trials. However, given that in signal detection theory the discrimination is between a signal+noise distribution and a weaker noise distribution, and that the level of noise relative to the signal could vary, differences in the relative "strengths" of the probes at different distances from the final location of the target or from the probe at the final location of target do not invalidate the analogy.

If mapping of stimulus categories and response categories in an experiment on representational momentum onto stimulus categories and response categories in an experiment on signal detection is possible, then methods from signal detection theory (e.g., measures of sensitivity [*d′*] and bias [ß]) could be applied to an examination of representational momentum. Just as varying prior probability in an experiment on signal detection allows examination of effects of sensitivity and bias on detection, varying prior probability in an experiment on representational momentum allows examination of effects of sensitivity and bias on displacement. Importantly, sensitivity or bias could in principle influence representational momentum regardless of the method of response collection, and so examination of potential sensitivity and bias is also relevant to studies of representational momentum that use other response measures (e.g., cursor-positioning, Hubbard & Bharucha, 1988; Hubbard & Ruppel, 2002; reaching, Ashida, 2004; Kerzel, 2003). Additionally, representational momentum has been hypothesized to reflect a decrease in sensitivity (Bertamini, 2002), and varying prior probability a *same* response would be correct allows explicit examination of the sensitivity hypothesis. Thus, any potential role of the prior probability a probe would be at the final location of a target in determining displacement is of broad theoretical importance in any general understanding of representational momentum.

In the experiments reported here, effects on displacement of manipulating actual prior probability or expected prior probability a *same* response to a subsequent probe of final target location would be correct on any given trial were examined. Participants were presented with implied leftward motion of a target or implied rightward motion of a target. After the target vanished, a probe slightly behind, the same as, or slightly beyond the final location of the target was presented. Participants judged whether the probe was at the same location where the target vanished or at a different location. In Experiment 1, prior probabilities of different probe positions varied across different groups of participants, and different groups of participants received trials in which a *same* response would have been correct on 10%, 30%, 50%, 70%, or 90% of the trials. Participants were not informed of these probabilities. This allowed examination of the influence of the actual prior probabilities on displacement. In Experiment 2, all participants received trials in which a *same* response would have been correct on approximately 11% of the trials (typical of previous studies of representational momentum), but instructions given to different groups of participants specified a *same* response would have been correct on 10%, 30%, 50%, 70%, or 90% of the trials. This allowed examination of the influence of the expected prior probabilities on displacement.

EXPERIMENT 1

The decrease in the probability of a *same* response in feedback conditions in Ruppel et al. (2009) suggested participants' responding was influenced by the low prior probability a *same* response would be correct. One way to examine this hypothesis is to compare participants' responding when prior probability a *same* response would be correct is relatively high (i.e., when a large proportion of trials present the probe at the final location of the target) with participants' responding when prior probability a *same* response would be correct is relatively low (i.e., when a small proportion of trials present the probe at the final location of the target). Accordingly, Experiment 1 presented different groups of participants with different sets of probe stimuli in which the proportion of trials for which a response of *same* would be correct varied. If Ruppel et al.'s speculation that participants' responding is influenced by prior probability a *same* response would be correct is accurate, then when prior probability a *same* response would be correct is decreased (1) the probability a participant would produce a *same* response on any given trial should be decreased, and (2) estimates of forward displacement should not change. In order to separate influences of expected prior probabilities (presumably consistent across groups) and actual prior probabilities (explicitly varied across groups), participants were not informed of the actual prior probability a *same* response would be correct (i.e., participants were not informed of the actual proportions of same trials and of different trials).

Method

Participants

The participants were 101 undergraduates who were naive to the hypotheses and received partial course credit in return for participation. Each participant was assigned to either the 10% probability group ($n = 20$), 30% probability group ($n = 20$), 50% probability group ($n = 21$), 70% probability group ($n = 20$), or 90% probability group ($n = 20$).

Apparatus

The stimuli were displayed upon and the data collected by an Apple iMac desktop computer equipped with a 15-inch colour monitor.

Stimuli

The moving target and probe were black square shapes 20 pixels (approximately 0.83 degrees of visual angle) in width and in height and were

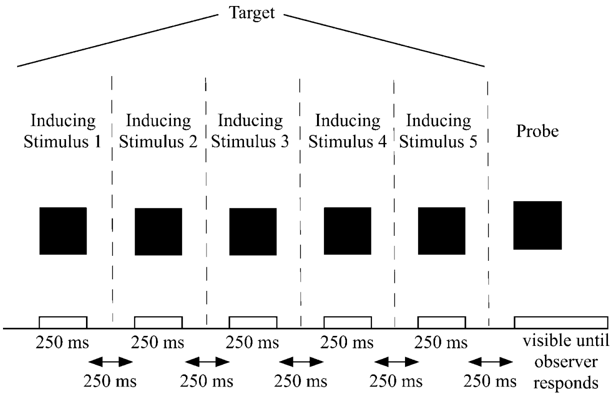

Figure 1. The structure of a trial in Experiment 1. There were five inducing stimuli that comprised the target; each inducing stimulus was presented for 250 ms, and there was a 250 ms ISI between successive inducing stimuli. The probe was presented after a retention interval of 250 ms, and remained visible until the participant responded. The horizontal dimension reflects when each stimulus was presented, and does not reflect the spatial arrangement of the stimuli.

presented on a white background. As shown in Figure 1, on each trial there were five successive presentations of the target that implied consistent rightward motion of the target or consistent leftward motion of the target. Consistent with previous studies of representational momentum, these presentations are referred to as *inducing stimuli*. Each inducing stimulus was presented for 250 ms, and there was a 250 ms interstimulus interval (ISI) between successive inducing stimuli. For rightward motion, the first inducing stimulus appeared approximately midway between the left side and the centre of the display, and the horizontal coordinates of each successive inducing stimulus were located 40 pixels (approximately 1.66 degrees of visual angle) to the right of the previous inducing stimulus; for leftward motion, the first inducing stimulus appeared approximately midway between the right side and the centre of the display, and the horizontal coordinates of each successive inducing stimulus were located 40 pixels to the left of the previous inducing stimulus. The vertical coordinates of the inducing stimuli were approximately centred along the vertical axis of the display.

The probe on each trial was presented at the same vertical coordinates as the moving target on that trial and was located at one of nine horizontal positions relative to the final location of that moving target: -12, -9, -6, -3, 0, $+3$, $+6$, $+9$, or $+12$ pixels. Probe positions denoted by a minus sign indicated the probe was shifted backward (i.e., in the direction opposite to target motion) from the final location of the moving target by the indicated number of pixels, and probe positions denoted by a plus sign indicated the probe was shifted forward (i.e., in the direction of target motion) from the final location of the moving target by the indicated number of pixels; the zero probe position was the same as the final location of the moving target. Probe positions denoted by a minus sign or a plus sign were considered different probes, and the zero probe position was considered the same probe.

10% probability group. For leftward motion, each of the eight different probes (−12, −9, −6, −3, +3, +6, +9, +12) was presented on nine trials, and the same probe was presented on eight trials; for rightward motion, each of the eight different probes was presented on nine trials, and the same probe was presented on eight trials. There were a total of 160 trials (144 in which a *different* response was correct, and 16 in which a *same* response was correct), and each participant received a different random order of trials.

30% probability group. For leftward motion, each of the eight different probes was presented on seven trials, and the same probe was presented on 24 trials; for rightward motion, each of the eight different probes was presented on seven trials, and the same probe was presented on 24 trials. There were a total of 160 trials (112 in which a *different* response was correct, and 48 in which a *same* response was correct), and each participant received a different random order of trials.

50% probability group. For leftward motion, each of the eight different probes was presented on five trials, and the same probe was presented on 40 trials; for rightward motion, each of the eight different probes was presented on five trials, and the same probe was presented on 40 trials. There were a total of 160 trials (80 in which a *different* response was correct, and 80 in which a *same* response was correct), and each participant received a different random order of trials.

70% probability group. For leftward motion, each of the eight different probes was presented on three trials, and the same probe was presented on 56 trials; for rightward motion, each of the eight different probes was presented on three trials, and the same probe was presented on 56 trials. There were a total of 160 trials (48 in which a *different* response was correct, and 112 in which a *same* response was correct), and each participant received a different random order of trials.

90% probability group. For leftward motion, each of the eight different probes was presented on one trial, and the same probe was presented on 72 trials; for rightward motion, each of the eight different probes was presented on one trial, and the same probe was presented on 72 trials. There were a total of 160 trials (16 in which a *different* response was correct, and 144 in which a *same* response was correct), and each participant received a different random order of trials.

Procedure

Participants were first given a practice session consisting of 10 practice trials randomly drawn from the experimental trials for their probability group. Participants pressed a designated key to begin each trial. The inducing stimuli appeared, and after the final inducing stimulus vanished, the retention interval between the disappearance of the final inducing stimulus and the subsequent appearance of the probe was 250 ms. After the probe appeared, participants pressed a key marked "S" or a key marked "D" (the "M" and "C" keys, respectively, of a standard keyboard) with the right or left index fingers, respectively, to indicate if the location of the probe was the same as or different from the final location of the moving target. Participants then initiated the next trial.

Results

Four types of analyses were conducted. The first type involved comparisons of same/different judgements of probes in different probe positions. The other three types involved different measures derived from the distributions of same/different judgements: Weighted mean estimates of displacement, hit rate and false alarm rates, and d' and ß.

Same/different judgements

The probabilities of a *same* response for each probe position are shown in Figure 2 and were analysed in a mixed-model ANOVA with probability (10%, 30%, 50%, 70%, 90%) as a between-subjects variable and probe (-12, -9, -6, -3, 0, $+3$, $+6$, $+9$, $+12$) as a within-subjects variable. Participants' responses were not influenced by the prior probability a *same* response would be correct, $F(4, 96) = 1.59$, $MSE = 0.21$, $p = .18$, but probability did interact with probe, $F(32, 768) = 1.46$, $MSE = 0.14$, $p < .05$. As shown in Figure 2, there was an increased probability of a *same* response for probe positions more distant from the final location of the target for the 90% group. As would be expected, probe influenced the probability of a *same* response, $F(8, 32) = 125.78$, $MSE = 0.14$, $p < .0001$, with participants more likely to respond *same* to probes located closer to the actual final location of the target.

Weighted means

Consistent with previous studies in the representational momentum literature (e.g., Freyd & Jones, 1994; Hubbard, 1993; Munger, Solberg, Horrocks, & Preston, 1999), estimates of direction and magnitude of displacement in remembered location were determined by calculating the

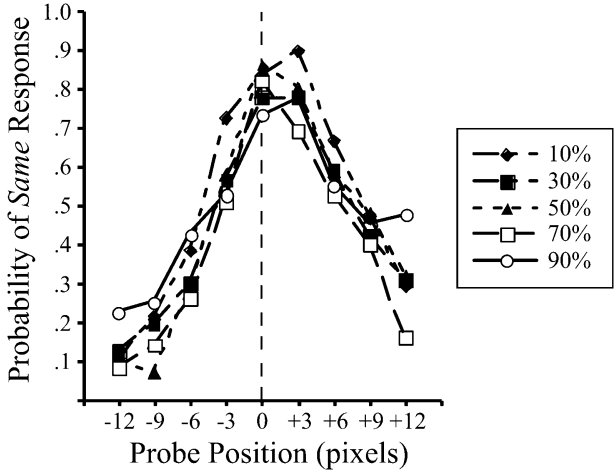

Figure 2. The probability of a *same* response for the 10%, 30%, 50%, 70%, and 90% probability groups as a function of probe position in Experiment 1.

arithmetic weighted mean (i.e., the sum of the products of the proportion of *same* responses and the distance of the probe from the final location of the moving target, in pixels, divided by the sum of the proportions of *same* responses) for each participant for each condition. The sign of a weighted mean indicated the direction of displacement (i.e., a minus sign indicated backward displacement in the direction opposite to target motion, a plus sign indicated forward displacement in the direction of target motion), and the absolute value of a weighted mean indicated the magnitude of displacement (i.e., larger absolute values indicated larger magnitudes of displacement). A weighted mean significantly larger than zero would indicate representational momentum occurred.

The weighted means were analysed in a one-way ANOVA with probability (10%, 30%, 50%, 70%, 90%) as a between-subjects variable. The weighted means were not influenced by the prior probability a *same* response would be correct, $F(4, 96) = 0.13$, $MSE = 5.17$, $p > .96$. Weighted means for the 10% ($M = 1.54$, $SE = 0.243$), $t(19) = 6.33$, $p < .0001$, 30% ($M = 1.61$, $SE = 0.366$), $t(19) = 4.38$, $p < .0003$, 50% ($M = 1.86$, $SE = 0.279$), $t(20) = 6.67$, $p < .0001$, 70% ($M = 1.59$, $SE = 0.406$), $t(19) = 3.92$, $p < .0009$, and 90% ($M = 1.64$, $SE = 0.458$), $t(19) = 3.57$, $p < .002$, probability groups were all significantly larger than zero (Bonferroni correction, $p < .05/5 = .01$). Thus, robust representational momentum occurred regardless of the actual prior probability a *same* response would be correct, and the magnitude of forward displacement was not influenced by the actual prior probability a *same* response would be correct on any given trial.

Hits and false alarms

Even though an analysis of hits and false alarms overlaps the analysis of same/different judgements, an analysis of hits and false alarms is presented for completeness. There are three different types of false alarms of potential interest. The first type is *FA-behind*, in which participants responded *same* to probes located behind the actual final location of the target. The second type is *FA-beyond*, in which participants responded *same* to probes located in front of the actual final location of the target. The third type is *FA-total*, which combined FA-behind and FA-beyond into a single category of false alarm. The existence of representational momentum predicts a higher occurrence of false alarms to probe positions in front of the actual final location of the target than to probe positions behind the actual final location of the target (i.e., FA-beyond > FA-behind). Given that a response of *different* on any given trial did not distinguish between positions behind the same probe and positions beyond the same probe, and that signal detection analyses usually do not distinguish between different types of false alarms (e.g., in calculation of d' and ß), a single measure reflective of both FA-behind and FA-beyond (i.e., FA-total) is also of interest.

Rather than a traditional analysis in which hit rate is analysed as a function of a single type of false alarm and plotted in a ROC diagram, it is more informative for the current issue to compare hit rate and false alarm rates across probability groups. Accordingly, hit rate and false alarm rates were analysed in a one-way ANOVA with probability (10%, 30%, 50%, 70%, 90%) as a between-subjects variable and performance (hits, FA-behind, FA-beyond, FA-total) as a within-subjects variable. Probability was not significant, $F(4, 96) = 1.31$, $MSE = 0.08$, $p = .27$, and least squares comparisons revealed the average of hit rate and false alarm rates for the 10% ($M = 0.56$, $SE = 0.027$), 30% ($M = 0.50$, $SE = 0.027$), 50% ($M = 0.52$, $SE = 0.030$), 70% ($M = 0.47$, $SE = 0.032$), and 90% ($M = 0.53$, $SE = 0.030$) probability groups did not differ. More trivially, performance was highly significant, $F(3, 12) = 235.74$, $MSE = 0.04$, $p < .0001$, and least squares comparisons of hits ($M = 0.80$, $SE = 0.016$), FA-behind ($M = 0.30$, $SE = 0.019$), FA-beyond ($M = 0.53$, $SE = 0.021$), and FA-total ($M = 0.42$, $SE = 0.017$) revealed all pairwise comparisons were highly significant.[2] As predicted, FA-beyond was higher than FA-behind. Performance interacted with probability, $F(12, 288) = 1.94$, $MSE = 0.02$, $p < .03$. As shown in Figure 3, hit rate did not

[2] The four levels of performance were not independent (FA-total is a linear combination of FA-behind and FA-beyond), and this violates an assumption of the ANOVA. However, the effect of performance is still highly significant even with the most conservative of error corrections. Also, it is useful to confirm that FA-behind is smaller than FA-beyond, and interesting that FA-behind and FA-beyond differ from FA-total.

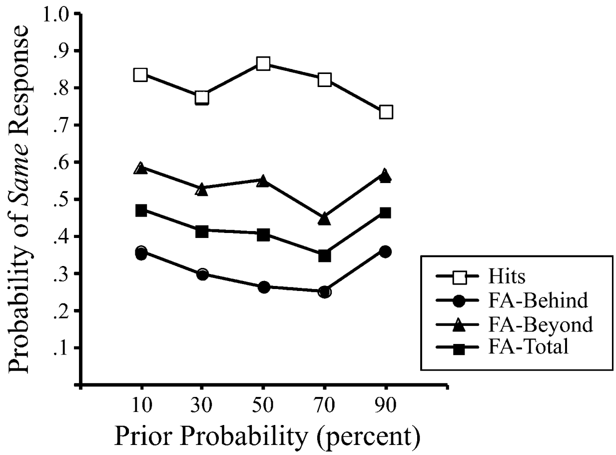

Figure 3. The probability of a *same* response for hits and false alarms (FA) as a function of prior probability in Experiment 1.

systematically vary with probability, but false alarm rates appeared to decrease between 10% and 70% and increase sharply between 70% and 90%.

d′ and ß

In signal detection theory, the sensitivity of a participant to whether a signal is present (i.e., in Experiment 1, whether a probe was at the same position as the final location of the target) is referred to as *d′*, and whether a participant's criterion for judging that a signal is present is relatively low or relatively high (i.e., in Experiment 1, whether a participant exhibited relatively more *same* responses or relatively more *different* responses across trials) is referred to as ß. Values of *d′* and ß based on hit rate and FA-total were calculated for each participant using standard procedures (e.g., see Macmillan & Creelman, 2004; McNicol, 2004; Wickens, 2001) and were analysed in separate one-way ANOVAs with probability (10%, 30%, 50%, 70%, 90%) as a between-subjects variable. Probability influenced *d′*, $F(4, 96) = 2.86$, $MSE = 0.57$, $p < .03$. Least squares comparisons revealed *d′* was smaller for the 90% probability group ($M = 0.80$, $SE = 0.135$) than for the 10% ($M = 1.32$, $SE = 0.210$), 30% ($M = 1.17$, $SE = 0.163$), 50% ($M = 1.45$, $SE = 0.139$), or 70% ($M = 1.52$, $SE = 0.181$) probability groups. Probability influenced ß, $F(4, 96) = 3.11$, $MSE = 0.14$, $p < .02$. Least squares comparisons revealed ß for the 10% ($M = 0.52$, $SE = 0.096$), 30% ($M = 0.65$, $SE = 0.073$), 50% ($M = 0.66$, $SE = 0.082$), and 70% ($M = 0.67$, $SE = 0.080$) probability groups were significantly less than ß for the 90% ($M = 0.92$, $SE = 0.078$) probability group.

Discussion

Participants exhibited robust representational momentum regardless of whether the actual prior probability a *same* response would be correct on any given trial was relatively low, moderate, or high. Importantly, weighted mean estimates of representational momentum were not influenced by the prior probability a *same* response would be correct. Although changes in prior probability a *same* response would be correct did not change the overall probability participants would generate a *same* response, probability group interacted with probe position such that for the highest probability group increases in prior probability increased the probability that participants would generate a *same* response to probe positions more distant from the target. An interaction of probability group and probe position, rather than a main effect of probability group, might have occurred because near ceiling rates of *same* responses for 0 and $+3$ probe positions decreased the effect of prior probability on judgements of 0 and $+3$ probe positions relative to the effect of prior probability on judgements of other probe positions. Decreases in the probability of a *same* response with decreases in prior probability for the majority of probe positions, as well as lack of an effect of prior probability on estimates of forward displacement, is consistent with speculation of Ruppel et al. (2009).

An analysis of hit rate and false alarm rates revealed that hit rate was significantly higher than were false alarm rates and that false alarm rates decreased with increases in the distance of the probe from the final location of the target. Such results are not surprising and confirm participants performed the experimental task at a greater than chance level. Additionally, false alarm rates to probes beyond the final location of the target were significantly higher than were false alarm rates to probes behind the final location of the target, and this pattern is consistent with representational momentum. More interestingly, changes in prior probability a *same* response would be correct did not systematically influence hit rate, but did lead to an increase in false alarm rates when prior probability a *same* response would be correct was relatively high. An increase in false alarm rates when prior probabilities a *same* response would be correct were increased is consistent with typical findings in signal detection theory (i.e., increases in false alarms when a target is more likely to be present). The patterns of hit rate and false alarm rates reflect that hit rate was already near ceiling, whereas false alarm rates could still increase. Increases in false alarm rates, coupled with a lack of change in hit rate, when the prior probability a *same* response would be correct increased are consistent with the interaction of probability group and probe position in the analysis of same/different judgements.

There was a significant effect of prior probability on d' and on ß, with lowest d' and highest ß occurring for the 90% probability group, and neither *d′* nor ß differed across other probability groups. The decrease in *d′* in the 90% probability group is consistent with the increase in false alarms and suggests participants in the 90% probability group were less sensitive to differences between same probes and different probes. This might have occurred if there was insufficient exposure to or practice with the different probes. The increase in ß for the 90% probability group is more puzzling, as an increased likelihood of a signal being present would usually be expected to decrease ß. It might be that participants initially assumed there should be an equal number of *same* responses and *different* responses, and so after some number of trials, participants in the 90% probability group adopted a criterion higher than that of other participants as a way to compensate for what they considered to be too many *same* responses; however, such an explanation does not initially seem consistent with the trend toward increases in false alarms unless it is further speculated that false alarms would have been even higher had such a high criterion not been adopted. Such an explanation involves differences between expected prior probabilities and actual prior probabilities, and this is further examined in Experiment 2.

EXPERIMENT 2

Experiment 1 varied the actual prior probability a *same* response would be correct on any given trial by giving all participants the same instructions but varying the set of probe stimuli across different groups of participants. However, in Ruppel et al. (2009) the introduction of feedback for some participants changed the instructions (potentially changing expected prior probabilities) but kept the set of probe stimuli (and actual prior probabilities) the same across different groups of participants. Also, variations in actual prior probability as in Experiment 1 might have less impact on participants' responding than would variations in expected prior probability, as participants might require some minimum amount of exposure to experimental stimuli (i.e., some minimum number of trials) before responding based on actual prior probabilities could occur. Accordingly, Experiment 2 varied the expected prior probability a *same* response would be correct on any given trial by varying instructions given to participants prior to data collection but giving all participants the same set of probe stimuli. For all participants, each probe position appeared an equal number of times across the course of the experiment (i.e., each probe position appeared on 1/9 of the total number of trials), but participants in the 10%, 30%, 50%, 70%, and 90% probability groups were instructed a response of *same* would be correct on approximately 10%, 30%, 50%, 70%, or 90% of the trials, respectively.

Method

Participants

The participants were 101 undergraduates from the same participant pool used in Experiment 1, and none had participated in Experiment 1. Each participant was assigned to either the 10% probability group ($n = 20$), 30% probability group ($n = 20$), 50% probability group ($n = 21$), 70% probability group ($n = 20$), or 90% probability group ($n = 20$).

Apparatus

The apparatus was the same as in Experiment 1.

Stimuli

The moving target and probes were the same as in Experiment 1, with the following exceptions: Each probe position was equally likely across the set of experimental trials (i.e., was presented on 1/9 of the trials). There were a total of 162 (2 directions × 9 probes × 9 replications) trials (144 in which a *different* response was correct, and 18 in which a *same* response was correct), and each participant received a different random order of trials.

Procedure

The procedure was the same as in Experiment 1, with the following exceptions: All participants received the same set of probes in which each probe position was equally likely to be presented across the set of experimental trials. Participants in the 10%, 30%, 50%, 70%, and 90% probability groups were instructed prior to the beginning of the trials that a response of *same* would be correct on 10%, 30%, 50%, 70%, or 90% of the trials, respectively.

Results

As in Experiment 1, analyses involving same/different judgements, weighted mean estimates of displacement, hit rate and false alarm rates, and d' and ß were conducted.

Same/different judgements

The probabilities of a *same* response for each probe position are shown in Figure 4 and were analysed in a mixed-model ANOVA with probability (10%, 30%, 50%, 70%, 90%) as a between-subjects variable and probe

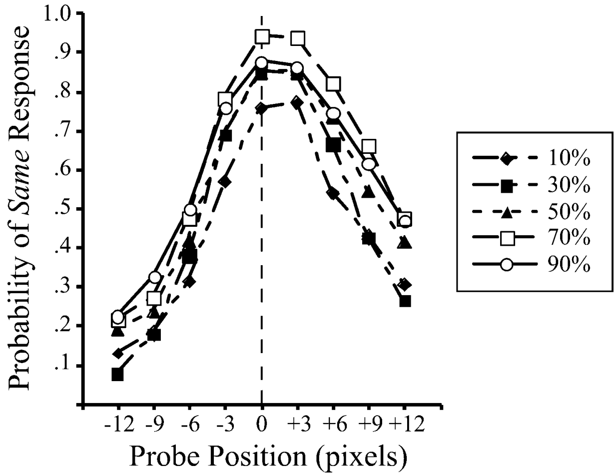

Figure 4. The probability of a *same* response for the 10%, 30%, 50%, 70%, and 90% probability groups as a function of probe position in Experiment 2.

(−12, −9, −6, −3, 0, +3, +6, +9, +12) as a within-subjects variable. Participants' responses were influenced by expectations (i.e., instructions) regarding the prior probability a *same* response would be correct, $F(4, 96) = 4.93$, $MSE = 0.20$, $p < .0012$. As shown in Figure 4, the amplitude of the distribution of *same* responses increased (i.e., there were more same responses) when participants expected the prior probability a *same* response would be correct was increased, and least squares comparisons revealed a *same* response was less likely in the 10% ($M = 0.44$, $SE = 0.018$) probability group than in the 50% ($M = 0.55$, $SE = 0.018$), 70% ($M = 0.62$, $SE = 0.018$), and 90% ($M = 0.60$, $SE = 0.019$) probability groups, and less likely in the 30% ($M = 0.49$, $SE = 0.018$) probability group than in the 70% and 90% probability groups. As would be expected, probe influenced the probability of a *same* response, $F(8, 32) = 212.92$, $MSE = 0.05$, $p < .0001$, with participants more likely to respond *same* to probes located closer to the actual final location of the target. Unlike in Experiment 1, the Probability × Probe interaction was not significant, $F(32, 768) = 0.87$, $MSE = 0.03$, $p = .67$. A comparison of Figures 2 and 4 suggests the distributions of *same* responses of different probability groups were more parallel in Experiment 2 than in Experiment 1, especially for probes more distant from the final location of the target.

Weighted means

The weighted means were calculated as in Experiment 1 and were analysed in a one-way ANOVA with probability (10%, 30%, 50%, 70%, 90%) as a between-subjects variable. The weighted means were not influenced by the expected prior probability a *same* response would be correct, $F(4, 96) = 0.40$, $MSE = 1.84$, $p > .98$. The weighted means for the 10% ($M = 1.65$, $SE = 0.298$), $t(19) = 5.54$, $p < .0001$, 30% ($M = 1.56$, $SE = 0.221$), $t(19) = 7.08$, $p < .0001$, 50% ($M = 1.69$, $SE = 0.355$), $t(20) = 4.76$, $p < .0001$, 70% ($M = 1.67$, $SE = 0.257$), $t(19) = 6.49$, $p < .0001$, and 90% ($M = 1.56$, $SE = 0.349$), $t(19) = 4.47$, $p < .0003$, probability groups were all significantly larger than zero (Bonferroni correction, $p < .05/5 = .01$). Thus, robust representational momentum occurred regardless of the expected prior probability a *same* response would be correct, and the magnitude of forward displacement was not influenced by expectations regarding the prior probability a *same* response would be correct.

Hits and false alarms

The hit rate and false alarm rates are shown in Figure 5 and were analysed in a one-way ANOVA with probability (10%, 30%, 50%, 70%, 90%) as a between-subjects variable and performance (hits, FA-behind, FA-beyond, FA-total) as a within-subjects variable. Probability was significant, $F(4, 96) = 5.27$, $MSE = 0.08$, $p < .0007$, and least squares comparisons revealed the average of hit rate and false alarm rates for the 10% ($M = 0.49$, $SE = 0.029$) probability group was less than for the 50% ($M = 0.59$, $SE = 0.026$), 70% ($M = 0.67$, $SE = 0.026$) and 90% ($M = 0.53$, $SE = 0.029$) probability groups, the 30% ($M = 0.56$, $SE = 0.026$) probability group was less than the 70% and 90% probability groups, and the 50% probability group was marginally less than the 70% probability group. As in Experiment 1,

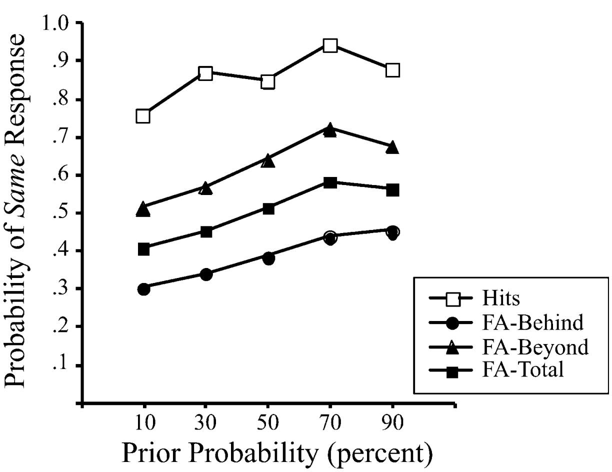

Figure 5. The probability of a *same* response for hits and false alarms (FA) as a function of prior probability in Experiment 2.

performance was highly significant, $F(3, 12) = 251.37$, $MSE = 0.02$, $p < .0001$, and least squares comparisons of hits ($M = 0.86$, $SE = 0.018$), FA-behind ($M = 0.38$, $SE = 0.018$), FA-beyond ($M = 0.62$, $SE = 0.021$), and FA-total ($M = 0.50$, $SE = 0.017$) revealed all pairwise comparisons were highly significant. Unlike in Experiment 1, the Performance × Probability interaction was not significant, $F(12, 288) = 0.63$, $MSE = 0.02$, $p < .82$. As shown in Figure 5, hit rate and false alarms increased with increases in the probability a *same* response would be correct.

d′ and ß

Values of *d′* and ß based on hit rate and FA-total were calculated as in Experiment 1 for each participant, and these values were analysed in separate one-way ANOVAs with probability (10%, 30%, 50%, 70%, 90%) as a between-subjects variable. Probability did not influence *d′*, $F(4, 96) = 0.61$, $MSE = 0.89$, $p < .65$, and no comparisons of the 10% ($M = 1.17$, $SE = 0.192$), 30% ($M = 1.49$, $SE = 0.172$), 50% ($M = 1.07$, $SE = 0.258$), 70% ($M = 1.38$, $SE = 0.243$), or 90% ($M = 1.26$, $SE = 0.161$) probability groups were significant. Probability influenced ß, $F(4, 96) = 3.16$, $MSE = 0.14$, $p < .02$. Least squares comparisons revealed ß for the 10% ($M = 0.65$, $SE = 0.088$) probability group was larger than ß for the 70% ($M = 0.25$, $SE = 0.068$) and 90% ($M = 0.42$, $SE = 0.083$) probability groups, ß for the 50% ($M = 0.50$, $SE = 0.091$) probability group was larger than ß for the 70% probability group, and ß for the 30% ($M = 0.44$, $SE = 0.074$) probability group did not differ from ß for the other probability groups.

Discussion

Participants exhibited robust representational momentum regardless of whether they expected the prior probability a *same* response would be correct on any given trial was relatively low, moderate, or high. Importantly, weighted mean estimates of representational momentum were not influenced by expectations regarding the prior probability a *same* response would be correct. These findings are consistent with the lack of an effect of actual prior probability on weighted mean estimates of displacement in Experiment 1. In Experiment 2, expectation of an increased probability a *same* response would be correct led to an increase in the probability of a *same* response, and both hit rate and false alarm rates increased with increasing probability a *same* response would be correct. These patterns are consistent with speculation of Ruppel et al. (2009). Also, increases in hit rates and in false alarm rates are consistent with the significant decrease in ß in Experiment 2 with increases in prior probability and with general decreases in criterion with increases in the likelihood a signal would be present usually found in signal detection analyses.

As in Experiment 1, hit rate was significantly higher than were false alarm rates, and consistent with representational momentum, false alarm rates to probes beyond the final location of the target were significantly higher than were false alarm rates to probes behind the final location of the target.

Expectations regarding the prior probability a *same* response would be correct did not influence *d′*. This is consistent with the possibility the decrease in *d′* in the 90% probability group in Experiment 1 was related to insufficient exposure to or practice with different probes, as participants in the 90% probability groups received 16 experimental trials with different probes in Experiment 1 but 144 experimental trials with different probes in Experiment 2. Expectations regarding the prior probability a *same* response would be correct influenced ß; when participants expected the prior probability of a *same* response was relatively high, ß was smaller than when participants expected the prior probability of a *same* response was relatively low. Even though there was a general trend for ß to decrease with increases in prior probability, there was a trend for ß to increase between the 70% probability group and the 90% probability group in Experiment 2, and this latter trend is consistent with Experiment 1 and the possibility that participants in the 90% probability groups in Experiments 1 and 2 subsequently adopted a stricter criterion in an attempt to decrease the number of *same* responses. The increase in ß in the 90% probability group was greater in Experiment 1 than in Experiment 2; this might reflect that participants in Experiment 2 had been explicitly instructed regarding prior probability, whereas participants in Experiment 1 might have initially assumed a more moderate prior probability.

GENERAL DISCUSSION

The methodologies and empirical findings of Experiments 1 and 2 are summarized in Table 1. In Experiment 1, the actual prior probability a *same* response would be correct varied across participants, but participants were not informed of the prior probability. Increases in the actual prior probability across different groups of participants increased the probability of a *same* response to probes more distant from the final location of the target when prior probability a *same* response would be correct was highest, but did not influence the probability of a *same* response in general or the weighted mean estimates of representational momentum derived from the distributions of *same* responses. Increases in the actual prior probability a *same* response would be correct across participants did not influence hit rate, but increased false alarm rates, and for participants who experienced the highest prior probability, decreased *d′* and increased ß. In Experiment 2, the actual prior probability a *same* response would be correct did not

TABLE 1
Summary of methodologies and empirical results

	Experiment 1	*Experiment 2*
Differences in prior probabilities	In probe set, not mentioned to participants	In instructions only; probe set constant for all participants
Same/different judgements	Probability × Probe interaction; participants more likely to respond *same* to more distant probes with increases in prior probability	*Same* responses increased with higher prior probability
Weighted means	No effect of prior probability; RM in all conditions	No effect of prior probability; RM in all conditions
Hits and false alarms	FA increased with highest prior probability; FA-beyond > FA-behind; hits > FA	Hits and FA increased with higher prior probability; FA-beyond > FA-behind; hits > FA
d′	Decreased with highest prior probability	No effect of prior probability
ß	Decreased with highest prior probability	Decreased with increases in prior probability

FA = false alarms. RM = representational momentum.

vary across participants, but different groups of participants were informed of different prior probabilities. Increases in the expected prior probability across different groups of participants increased the overall probability participants would generate a *same* response, but did not influence the weighted mean estimates of representational momentum derived from the distributions of *same* responses. Increases in the expected prior probability a *same* response would be correct across participants increased hit rate, increased false alarm rates, and decreased ß, but did not influence *d′*.

Manipulation of actual prior probability in Experiment 1 or of expected prior probability in Experiment 2 did not influence weighted mean estimates of representational momentum, but did influence the probability of a *same* response for probe positions more distant from the final location of the target (Experiment 1) or for all probe positions (Experiment 2). A stronger and clearer effect of prior probability was observed in Experiment 2 than in Experiment 1. Participants in Experiment 1 were not informed of the prior probability and so presumably required some minimum number of experimental trials before their responding might be adjusted to reflect actual prior probability, whereas participants in Experiment 2 were informed of the prior probability and so presumably adjusted their initial expectations before the experimental trials began.[3] Thus, effects of prior probability in Experiment 1 were potentially diluted by having responses to experimental trials prior to when participants' responses were adjusted to reflect actual prior probability averaged with responses to experimental trials subsequent to when participants' responses were adjusted to reflect actual prior probability. Also, presenting a set of probe stimuli as in Experiment 2 which was constant across participants, and in which each probe was equally likely across the set of experimental trials, is consistent with the methodology in a majority of previous experiments on representational momentum. Given the lack of an effect of prior probability on displacement in Experiments 1 and 2, researchers can have greater confidence in use of the probe methodology for obtaining estimates of displacement.

Measures of d' were influenced by actual prior probability in Experiment 1, but were not influenced by expected prior probability in Experiment 2. As d' measures sensitivity, this pattern is consistent with the notion in signal detection theory that sensitivity per se is not influenced by expectations of an observer, as significant differences in d' occurred in Experiment 1 (in which probe stimuli differed and instructions regarding prior probability did not differ across groups of participants) but did not occur in Experiment 2 (in which probe stimuli did not differ and instructions regarding prior probability did differ across groups of participants). Even so, the significant effect of prior probability on d' in Experiment 1 was driven by the low d' in the 90% probability group, and none of the other probability groups were significantly different, nor was there a consistent trend across the other probability groups. If representational momentum generally resulted from a decrease in sensitivity (cf. Bertamini, 2002), the weighted mean estimates of displacement should have been influenced by d' and a consistent trend across all probability groups should have been observed in both Experiments 1 and 2. Thus, the decrease in d' in the 90% probability group in Experiment 1 might simply be an outlier. Alternatively, this decrease might reflect an artificially low level of

[3] It is possible that participants in Experiment 2 also adjusted their responding to reflect the actual prior probabilities; that is, the probability that participants would generate a *same* response on any given trial in Experiment 2 might have changed if participants began to suspect the probability of a *same* response being correct did not correspond with the instructions they had received. Even so, given explicit mention of prior probabilities in the instructions in Experiment 2 and the lack of explicit mention of prior probabilities in the instructions in Experiment 1, such adjustment would presumably have occurred later in Experiment 2 (i.e., evidence from more trials was required) than in Experiment 1, and so effects of such adjustment would be smaller in Experiment 2 than in Experiment 1. Also, each participant in Experiment 1 or 2 received a different random order of trials, and so even if such adjustment in responding occurred, effects of such adjustment would be randomly distributed across trial types.

performance resulting from exposure to an insufficient number of different probes.

Measures of ß were influenced by actual prior probability in Experiment 1 and by expected prior probability in Experiment 2. As ß measures bias, this pattern is consistent with the notion that participants' responses reflect a type of bias. However, even though the type of bias measured by ß influenced probability of a *same* response, such a bias did not influence representational momentum. More specifically, the type of bias measured by ß influenced amplitudes of the distributions of the probability of a *same* response as a function of probe position (i.e., amplitudes of tails of distributions in Experiment 1, amplitudes of entire distributions in Experiment 2), but did not influence forward-shifted asymmetries of the distributions of the probability of a *same* response as a function of probe position. This pattern is consistent with speculation in Ruppel et al. (2009) that the decrease in the amplitude of a distribution of *same* responses during or after a block of trials in which feedback had been presented resulted from participants learning (within some number of trials after beginning to receive feedback) the prior probability a *same* response would be correct on a given trial was relatively low (1/7). In general, effects of expected differences in prior probability on ß in Experiment 2 were clearer and stronger than were effects of actual differences in prior probability on ß in Experiment 1, and this is consistent with the notion ß reflects participants' criteria for responding rather than sensory variables per se.

Given that in representational momentum memory for the target is displaced in a consistent direction relative to target motion, such a displacement might be considered a bias rather than a random error or noise. However, this use of the term "bias" seems inconsistent with the finding that changes in prior probability or in ß were not linked with changes in representational momentum. This inconsistency can be resolved if a distinction is introduced between *performance bias* and *competence bias.* Paralleling the performance/competence distinction introduced in psycholinguistics by Chomsky (1957), performance bias in displacement involves the response and reflects actual performance on a given trial and incidental variables such motivation, fatigue, and expectations about prior probability, whereas competence bias in displacement involves the encoding or storage and reflects general knowledge regarding objects and motion that is necessary to produce systematic displacement. Performance bias is more mutable and is reflected by ß, and different levels of such bias might be exhibited by different participants or in different circumstances; competence bias is less mutable and is not reflected by ß, but instead reflects a more fundamental property or characteristic of a cognitive structure or process.[4] Relating this distinction to data from Experiments 1 and 2, performance bias influences the amplitude of the distribution of *same* responses as a function of probe position, whereas competence bias influences the asymmetry of the distribution of *same* responses as a function of probe position.

The insensitivity of representational momentum to prior probability in Experiments 1 and 2 might seem inconsistent with results of numerous previous studies that found displacement is influenced by participants' expectations (for review, see Hubbard, 2005). However, previous studies manipulated actual or expected behaviour of the target, whereas prior probabilities examined in Experiments 1 and 2 manipulated actual or expected behaviour of the probe. The probe was a separate object presented after the target had already vanished, and so information regarding the probe (e.g., prior probability a *same* response would be correct) and that was not a cause or a consequence of the target or of target motion might be less likely to influence representational momentum for that target. Even though prior probability might influence the decision of whether to make a *same* response or a *different* response on any given trial, prior probability presumably does not influence the representation of the target or of the target trajectory (and so prior probability influences the amplitude, but not the asymmetry, of the distribution of *same* responses). Such a notion is generally consistent with findings that attempts to eliminate forward displacement by providing feedback regarding judgement of probes (Ruppel et al., 2009) or informing participants about representational momentum prior to experimental trials and asking them to adjust their responses to compensate for representational momentum (Courtney & Hubbard, 2008) have not been successful.

Effects of actual prior probability or expected prior probability a *same* response to a subsequent probe of target location would be correct did not influence forward displacement in memory for the final location of a moving target. Although prior probability a *same* response would be correct on any given trial influenced the overall probability of a *same* response, prior

[4] The distinction between performance bias and competence bias is also consistent with speculation that displacement might result from a combination of at least two different mechanisms (e.g., Hubbard, 2006). In this view, one mechanism is modular and cognitively impenetrable to a participant's beliefs, knowledge, and expectations regarding that target, and this type of mechanism reflects competence bias. The other mechanism is nonmodular and cognitively penetrable to a participant's beliefs, knowledge, and expectations regarding that target, and this type of mechanism reflects performance bias. Also, theories that suggest forwards displacement results from spatiotemporal coherence (Freyd, 1987) or a second-order isomorphism between subjective effects of physical principles and mental representation (Hubbard, 2006) posit a type of competence bias.

probability did not influence the greater likelihood of a *same* response to probes beyond the final location of the target than to probes behind the final location of the target. The data are consistent with the hypothesis that changes in expectations regarding prior probability a *same* response would be correct could account for the decrease in probability of a *same* response in Ruppel et al. (2009) and provide useful validation of the probe methodology in many previous studies of representational momentum. Furthermore, the data are not consistent with the hypothesis representational momentum generally results from a lack of sensitivity or from a performance bias. Also, introduction of a distinction between performance bias and competence bias, as well as novel application of signal detection methods and concepts to the types of psychometric functions obtained in Experiments 1 and 2, suggest significant constraints on and extensions to signal detection theory. Overall, the findings reported here underscore the robustness of representational momentum and present new ideas regarding use of signal detection theory and of bias in mental representation.

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