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Abstract

A variety of phenomena related to the oblique regions of space have been observed across modality and across domain. For instance, the classic 'oblique effect' describes a deficit in visual acuity for oriented lines in the oblique regions of space, and classic 'prototype effects' describe a bias to mis-localize objects towards the oblique regions of space. While there has been speculation that some 'oblique-related effects' share a common mechanism, many of these effects are explained in very different terms. The visual oblique effect itself is often understood as arising from coding asymmetries in orientation-selective neurons in the brain, whereas motor oblique effects have been described as arising from gravitational cues and/or physical limitations of the arm. Are these really distinct effects? Here, we show that individuals show stable oblique biases across these two modalities, suggesting that these effects may have a common cause.

Keywords: vision; perception; action; oblique effect; spatial cognition

Introduction

The oblique effect describes the phenomenon whereby observers are worse at discriminating oriented bars presented in the oblique (diagonal) regions of space compared to the cardinal (horizontal/vertical) regions. It is one of the most robust psychophysical effects ever studied. But what is the nature of the oblique effect? Typically conceived as a bias of orientation, it has traditionally been explained by appeal to coding asymmetries in orientation-selective neurons in the visual cortex (e.g., Li et al., 2003). However, a range of related effects have been observed not just in orientation judgment tasks, but also in location judgment tasks (Yousif et al., 2020), location placement tasks (Huttenlocher et al., 1991), various haptic/motor tasks (e.g., Gentaz & Hatwell, 1995; Gordon et al. 1995; Smyrnis et al., 2007), and even various aesthetic judgment tasks (Latto et al., 2000; Latto & Russell-Duff, 2002; Plumhoff & Schirillo, 2009; Youssef et al., 2015). Moreover, 'oblique-related' effects come in several different forms: Some of these effects are about reduced visual *acuity* in the oblique regions of space (e.g., Appelle, 1972; Yousif et al., 2020), whereas others involve memory errors and mis-localizations *towards* the oblique regions. Some involve vision (Huttenlocher et al., 1991; Latto et al., 2000; Yousif et al., 2020), while others are observed in the absence of visual input (e.g., Gentaz & Hatwell, 1995; Gordon et al., 1995; Smyrnis et al., 2007). Finally, some effects are characterized as attraction to certain regions of space, whereas others are characterized as effects of repulsion (see, e.g., Huttenlocher et al., 1991; Rademaker et al., 2017; Wei & Stocker, 2015). Do all of these effects reflect one underlying phenomenon, or many?

Surprisingly, these biases are often explained in radically different ways. While the standard visual oblique effect is explained by variance in neural representations across specific orientations (see, e.g., Furmanski & Engel, 2000; Li et al., 2003; see also Nasr & Tootell, 2012), oblique biases in spatial localization tasks have traditionally been explained by categorical effects of spatial representation (Huttenlocher et al., 1991). Meanwhile, oblique effects in haptic perception have been linked to gravitational cues (Gentaz & Hatwell, 1995) and oblique biases in motor responses (e.g., reaching) have been explained by the physical constraints of the human arm (Gordon et al., 1995).

Here, we consider the possibility that visual and motor oblique effects have a common cause.

The Oblique Effect(s)

The oblique effect typically refers to the phenomenon whereby observers, human and non-human, are faster and better at discriminating oriented lines near the cardinal axes as opposed to the oblique axes (Appelle, 1972; Bonds, 1982). That is, a line oriented at, say, 3˚, would be more readily discriminated from a line at 1˚ versus lines oriented at 48˚ and 46˚. This phenomenon is well-replicated and exceptionally robust (see, e.g., Essock, 1980; Vogels & Orban, 1985; Furmanski & Engel, 2000). More recent work on the oblique effect has focused on the nitty-gritty details of its implementation; for instance, there has been considerable interest in the reference frames over which the oblique effect operates (e.g., Cecala & Garner, 1986; Luyat et al., 2001; Luyat et al., 2005; Luyat & Gentaz, 2002; Rademaker et al., 2017).

There is consensus that the oblique effect is well-understood: It is thought that the oblique effect arises directly from the number of orientation-selective neurons devoted to processing certain orientations (Furmanski & Engel, 2000; Li et al., 2003; see also Nasr & Tootell, 2012). In other words, the idea is that there are more neurons specifically tuned for cardinal (and cardinal-adjacent) orientations than there are for oblique (and oblique-adjacent) orientations, likely reflecting the natural image statistics of the environment (Keil & Cristobal, 2000; Girshick, Landy, & Simoncelli, 2011; Henderson & Serences, 2021; Wei & Stocker, 2015).

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However, there are a number of effects not specific to visual orientation perception that involve biases near the oblique regions of space. For instance, simple location memory tasks reveal strong biases *towards* the obliques (Huttenlocher et al., 1991). Huttenlocher and colleagues (1991) famously proposed that spatial localizations simultaneously depend on 'coarse' and 'fine-grained' representations, the former of which is dictated by higher-level spatial knowledge. They proposed that biases towards the oblique axes reflected a bias towards the 'prototype' – the center of the quadrant in which the point originated (see subsequent work on the 'Category Adjustment Model'; Holden et al., 2010; Holden et al., 2013). While not mutually exclusive with this category-based explanation, recent work has shown that, coincidentally, angular acuity for the location of visually presented dots is lower near the oblique axes of space (Yousif et al., 2020). This raises the possibility that a reduction in angular acuity for object position at the obliques may be related to the placement biases first observed by Huttenlocher and colleagues.

The story is further complicated by the fact that oblique effects have been observed in other modalities. Indeed, there are biases in both touch and motor control that resemble visual oblique effects. For instance, there is an analogous "motor oblique effect" (i.e., a bias for motor movements to err towards the oblique regions of space; Gordon et al. 1995; Gourtzelidis et al. 2001; Mantas et al., 2008; Petersik & Pantle, 1982; Sainburg et al. 1995; Smyrnis et al., 2007) as well as a "haptic oblique effect" (i.e., a reduced ability to discriminate angled rods based on haptic information in the absence of vision; e.g., Gentaz & Hatwell, 1995). Are all of these biases – visual, somatosensory, and motor – connected in some way?

Current Study

Here we explore the possibility that various known oblique biases result from a singular deficit in acuity at the obliques, one that is stable across contexts. We reveal stable individual differences in oblique biases across both visual and motor tasks.

Experiment 1

Other than the oblique effect itself, perhaps the second most-well-known 'oblique-related' effects are biases of spatial localization towards the oblique regions of space, away from the cardinal axes (Huttenlocher et al., 1991; Yousif et al., 2020; Wei & Stocker, 2015). Rather than being explained by differences in angular acuity, though, these biases are traditionally described as arising from a categorical bias — a tendency to place points towards the center of the 'category' (often, a quadrant of Cartesian space) in which they originated. Here, we ask whether these localization biases — like the oblique effects in the previous experiment — are more general in nature. Specifically, we ask whether they are stable across modality. Participants will complete two separate tasks: A visual localization task (in which they remember and recreate locations based on visual input) and a motor localization task (in which they remember and revisit locations based on kinesthetic input). As with the previous experiment, we are asking whether we observe oblique biases in both tasks, and, if so, whether those biases are related.

Method

This experiment consisted of two separate tasks. One was a visual localization task in which participants saw dots briefly presented on a computer screen and, after a delay, had to recreate the location of that dot relative to a landmark. The other was a motor (proprioceptive) localization task in which participants were passively guided by a motorized robot to a location in space (sans any visual input) and, after a delay, had to move the robotic arm back to that location.

Participants 40 undergraduate students participated in exchange for course credit. Half of the participants completed the visual localization task first, and the other half completed the motor localization task first. Four additional participants were excluded prior to further data analysis based on predetermined exclusion criteria (three because of their responses during the debriefing survey; one because their overall accuracy was low).

Procedure and Design The visual localization task was modeled after the tasks used by Yousif & Keil (2021). Participants saw a blue target dot (10 pixels in diameter) presented in a random location relative to a central grey dot (25 pixels in diameter). The dots could *not* appear further than 120 pixels away from the central grey dot, nor could they appear within 30 pixels of the central grey dot. The dots would appear on the screen for 1500ms before disappearing. After another 500ms, the grey dot would reappear in a different location and the blue dot would be absent. The participants were asked to place a new blue dot to match the location of the previous dot, relative to the current grey dot. The central grey dot would initially appear in one of the four quadrants (always 250 pixels away from the center of the screen horizontally, and 150 pixels away from the screen vertically); the grey dot would always reappear in the opposite quadrant from where it had been initially. The initial position was counterbalanced so that the grey dot appeared in each quadrant an equal number of times. Once participants had clicked a single time, a blue dot would appear. However, participants could drag and drop or click additional times to replace the blue dot as they wished. They had an unlimited amount of time to respond, although they were encouraged to respond as quickly and as accurately as possible. To submit their responses, they pressed the spacebar. There were 120 trials in total. Participants completed two representative practice trials before beginning the task.

The motor localization task was designed to be as similar as possible to the localization task. Participants sat at a desk in front of a robotic manipulandum (henceforth referred to as the 'robot arm'; Kinarm Endpoint, Ontario Canada). The robot arm could be dragged by the participant, but it could also move autonomously (thus dragging the participant's

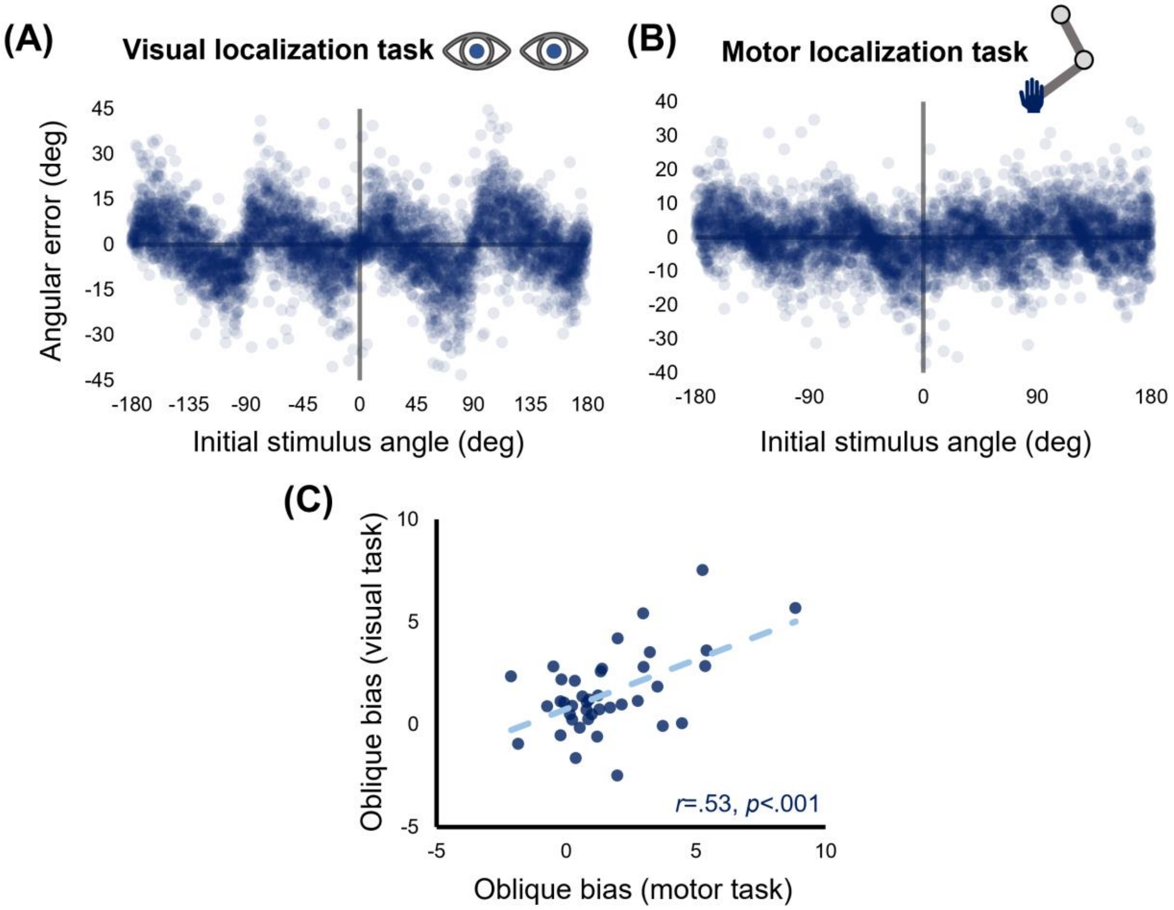

Figure 1. The overall patterns of errors for the visual localization task (A) and the motor localization task (B). The correlation between oblique biases across tasks is depicted in (C).

hand with it). Participants wore a black 'bib' that obfuscated their vision of the robot arm and the desk itself. However, they were able to see visuals which displayed helpful information throughout the task (e.g., signals for when they could respond, start the next trial, and so on); these minimal stimuli/prompts were reflected from a horizontally mounted LCD screen onto a semi-silvered mirror positioned below it (the mirror provided further visual occlusion, thus making the full arm and hand invisible to participants).

Each trial began with a grey dot presented centrally on the screen. During this portion of the task only, there was a small cursor (a white dot) that corresponded to the location of the participants hand on the desk below. Participants were told to move the cursor onto the central dot to begin the trial. As soon as they did this, both the central grey dot and the cursor would disappear. At this time, the robot arm would move the participant's hand to a random location in the 2D workspace. The random location could not be more than 7cm away from the center in each dimension (so that the maximum distance any point could be from the center was ~10cm), nor could it be within 3cm of the center in each dimension. The robot arm would guide the participant's hand directly to the location on each trial (this passive movement was designed to always take 1000ms), pause for 1000ms, then return to the center. After another 500ms, a green dot would appear on the screen, which signaled to participants that they could respond. Participants were instructed to move immediately and directly to the point that had been indicated by the robot. After the robot detected no significant movement (velocity <.5cm/s) for 500ms, it would register the participant's current hand position as the response on that trial. At this point, the cursor and central grey dot would reappear, and the participant could control the cursor to return to the home location and begin the next trial.

Participants were explicitly told prior to the task that they should not rely on any special strategies or heuristics to localize the points in space. Instead, they were told to rely only on their sense of space, even if it meant they were slightly less accurate. This was done to prevent participants from surreptitiously using strategies like placing their arm against the table or pressing it against their body and trying to remember how their arm had been positioned, rather than the locations themselves. As with the visual localization task, participants completed 120 trials. They completed 8 representative practice trials before beginning the task, during which they were given extensive verbal feedback (about the task itself, not their accuracy) to ensure that they understood the task.

Results and Discussion

The full data set for each task is displayed in Figure 1. As is evident from the figure, there were robust oblique biases that resemble those observed in prior work (e.g., Huttenlocher et al., 1991; Yousif et al., 2020). There are many ways to quantify these biases. One simple metric is to simply count all the trials in which participants erred towards the oblique axis vs. towards the cardinal axis. For the visual localization task, an average of 72% of trials (*SD*=.07) moved towards the oblique axes, *t*(39)=20.07, *p*<.001, *d*=3.25. For the motor localization task, an average of 59% of trials (*SD*=.07) moved towards the oblique axes, *t*(39)=8.14, *p*<.001, *d*=1.29. We can also quantify the magnitude of these biases: Are errors that move towards the oblique axes *larger* than errors that move towards the cardinal axes? For the visual localization task, the errors towards the oblique axes were an additional 3.91 degrees larger on average (points moving toward oblique: *M*=8.81deg, *SD*=2.29deg; points moving toward cardinal: *M*=4.91deg, *SD*=1.74deg; *t*(39)=14.71 *p*<.001, *d*=2.33). For the motor localization task, the errors towards the oblique axes were an additional 1.37 degrees larger on average (points toward oblique: *M*=6.39deg, *SD*=1.23deg; points toward cardinal: *M*=5.02deg, *SD*=1.33deg; *t*(39)=6.66, *p*<.001, *d*=1.05). These analyses confirm what is evident from Figure 1: Participants exhibited a robust tendency to err towards the oblique axes. For the remainder of this section, we'll refer to this analysis as 'differences-by-error-direction'.

Separately, we quantified the magnitude of angular errors for points that originated near the cardinal axes vs. those that originated near the oblique axes (unlike the previous analysis, which was based on where points erred towards, not where they originated). For the remainder of this section, we'll refer to this analysis as 'differences-by-origin-point'. For the visual localization task, errors were on average 1.26 degrees larger for points that originated near the cardinal axes, *t*(39)=4.40, *p*<.001, *d*=.70; for the motor localization task, errors were on average 1.19 degrees larger for points that originated near the cardinal axes, *t*(39)=6.19 *p*<.001, *d*=.98. Combined with the previous analysis, these results suggest that points originating near the cardinal axes (1) tend to move towards the oblique axes and (2) tend to move farther than points which had originated near the oblique axes.

Are the oblique biases we observed in each task related to one another? Surprisingly, there was no correlation between the magnitude of errors that moved towards the oblique axes (Pearson's *r*=.07, *p*=.68, 95% CI = [-0.33, 0.38]; Spearman's *r*=.09, *p*=.55, 95% CI = [-0.25, 0.32]). Crucially, however, there was a significant correlation between the magnitudes of errors that originated near one axis vs. the other (i.e., the difference in angular error between points that originated near the cardinal axes vs. near the oblique axes; Pearson's *r*=.53, *p*<.001, 95% CI = [0.06, 0.57]; Spearman's *r*=.39, *p*=.014, 95% CI = [0.03, 0.49]).

Consider what it means to observe any correlation between these tasks: The values being correlated here are *differences* in angular accuracy between two different regions of space, in two different modalities and in two different spatial planes (vertical in the visual task, horizontal in the motor task). This means that participants that happen to make larger errors near the cardinal axes in a visual localization task also happen to make larger errors near the cardinal axes in a completely nonvisual proprioceptive/motor localization task. This relation cannot be parsimoniously explained by purely visual or purely motor biases alone. It also cannot be explained by general inattention or inaccuracy, as there is no reason that errors due to attention or low effort should be localized to specific regions of space (except if a genuine oblique bias exists, as we propose). Thus, these results appear to reflect an oblique bias that arises from a modality-general system of spatial representation.

General Discussion

Here, we have proposed that visual and motor oblique biases may both be explained by a shared, underlying spatial representation. Whereas prior work has explained these phenomena in radically different terms, here we argue that nearly all these effects may share a common cause — a deficit in angular acuity in the oblique regions of space that is not specific to any modality or domain.

What does it mean to share a common format?

Some of the effects we have discussed here seem obviously related; indeed, some of them — the 'oblique effect', the 'haptic oblique effect', and the 'motor oblique effect' — share a common name. Thus, it seems relatively uncontroversial to say that these biases share a common basis. Some of these effects have long been understood in radically different ways, however. Perhaps the best example of this is the well-known spatial localization bias, whereby people misplace objects closer to the oblique axes than they were (Huttenlocher et al., 1991; Yousif et al., 2020). These effects, while obviously reminiscent of the oblique effect in some way, have been explained by appeal to a *cognitive* bias, not a perceptual one. Huttenlocher and colleagues famously argued that localization errors result from biases of categorization, a 'coarse' representation of location that is biased towards the 'prototype' of the initial category. The view presented here does not present evidence against that explanation — it continues to be plausible that categorical biases of spatial localization exist — but does offer an alternative way of understanding these localization biases. Specifically, we argue that it is possible that these biases arise not only from discrete, categorical biases but instead from continuous variation in angular acuity (see also Yousif et al., 2020). In practice, this means that the same system for spatial representation that biases your visual impression of an oriented line (as in the classic oblique effect) may also be responsible for biasing where you remember something being positioned in space (as in the work of Huttenlocher et al., 1991).

Perhaps even more striking is the fact that these effects span multiple modalities, including vision (Huttenlocher et al., 1991; Yousif et al., 2020), proprioception (Gentaz & Hatwell, 1995), and action (e.g., Baud-Bovy & Viviani, 2004; Gordon et al., 1995; Smyrnis et al., 2007). We observed robust correlations between oblique biases in two distinct modalities (i.e., vision, action). The consistency in these biases across disparate contexts opens the door to a provocative conclusion: that beneath these wide range of situations is a single shared representation for representing spatial information. As obvious as this conclusion may seem when stated this way, it is important to remember how differently many of these phenomena have been explained historically. And while others have speculated about a connection between visual and motor effects before (see, e.g., Baud-Bovy & Viviani, 2004), this is the first work to our knowledge to actually demonstrate direct relationships among these disparate modalities.

Putting this all together: We propose that the well-known, thought-to-be-well-understood oblique effect is *neither* an effect only of vision *nor* an effect only of orientation (despite classic explanations that appeal to both vision and orientation, e.g., Furmanski & Engel, 2000; Li et al., 2003). Moreover, well-known localization biases (e.g., 'prototype effects') are also neither about vision nor about localization. Likewise for the haptic and motor oblique effects. All of these biases may instead reflect a deeply *spatial* phenomenon — one that transcends modality.

Other accounts of related phenomena

In addition to the work discussed so far, there is one other recent paper that offers a general account of spatial biases. Based on localization errors in a serial reproduction task (in which one participant's output is presented to another participant as input, much like the game of telephone), Langlois and colleagues (2021) argue that spatial errors are biased towards the regions of an image which are represented with the *highest* acuity. This is of course at odds with perhaps the most famous spatial bias of all (i.e., prototype effects; Huttenlocher et al., 1991), which involves mis-localizations towards the regions of *lowest* acuity (i.e., the obliques; see Yousif et al., 2020; Wei & Stocker, 2015). Could both things be true at the same time? How would the current data be explained by Langlois and colleagues (2021)?

The phenomena studied and discussed throughout this paper are ones that occur in the absence of any sort of landmark. In the classic work of Huttenlocher and colleagues (1991), participants were simply tasked with remembering the location of a dot with respect to a larger circle. These same sorts of biases emerge even when participants localize a dot relative to a single other dot (Yousif et al., 2020) in the absence of any other visual information that could be used to guide the judgment. This is in stark contrast to the stimuli used by Langlois and colleagues, which consist entirely of naturalistic images (e.g., of a plane, a lighthouse, or a face). This is tantamount to the difference between navigating in an open field vs. in a dense city. When navigating in a city — with copious landmarks and clearly labeled streets — people will call on all of the available information to localize things in space. When giving directions in cities, for instance, people will frequently say things like, "Go over to 24th then up to Spruce past the grocery store, then turn right." But there are not landmarks or street names in a corn field. The sort of spatial representation we use to navigate in complex environments (i.e., a form of representation that depends on propositional knowledge of the environment) is very different from the sort of spatial representation that we use to navigate in more sparse environments (i.e., a form of representation that is influenced by perceptual input, independent of propositional knowledge as much as possible). So it is with the sorts of localizations considered here and by Langlois and colleagues (2021). We are here interested in the latter kind of representations — ones that arise from sparse input.

The format of spatial representation(s)

Although the evidence is indirect, it seems noteworthy that the acuity differences and biases we observe are not just about one region of space versus another, but also about one *dimension* of space versus another. The biases we observe are specific to *angular* acuity. This fact alone has some surprising implications. For instance, it means that the classic 'prototype effects' (Huttenlocher et al., 1991) may be conceived not just as biases towards a point in space, but as biases towards an axis of space along a single dimension. It also forces the conclusion that angular information is being represented independently from other dimensions on some level. Because of this, it may follow that the mind is likely to be representing spatial information in some sort of polar coordinate system. Indeed, analyses of errors like those studied here have revealed that polar error are independent from distance errors (while errors in cartesian dimensions are not independent from one another), lending further support for this conclusion (see Yousif & Keil, 2021; Yousif, 2022).

Conclusion

What do oblique effects in orientation judgments, pointing errors, visual memory errors, and angle-size judgments all have in common? While prior work has offered many different domain- and modality-specific explanations for these phenomena, ranging from cognitive biases to physical limitations, we suggest that they may all boil down to a single representational distortion: deficits in angular acuity in the oblique regions of space. These findings hint that beneath a wide range of observed phenomena exists a general, flexible, shared system of spatial representation.

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