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The Stages of Processing of One's Environment

by

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Dedication

Thank you so much to all of my family and friends that listened to my rants and pretended to understand my napkin graphs over the past few years. With everything I have, I have to acknowledge my mother for never once wavering in her faith despite my tendency to do just that. And, I would be remiss if I did not thank Lindsey. Her belief in me and this project was unrelenting. To all of you named here and otherwise: Thank you.

Abstract

Research on all tested vertebrates indicates that geometric information plays a special role when organisms reorient in their environment. Some researchers have argued that geometric information is processed automatically, while landmark information is processed more slowly. These conclusions of the course of reorientation processing have been drawn from research that tested organisms' accuracy in locating targets in experimental environments. However, inferences of the course of processing are not logical extensions of physical reorientation paradigms. To this end, the present research employs the psychological refractory period paradigm to investigate, over two experiments, the precise stages of processing that humans utilize when encoding an environment. The data confirm previous research by demonstrating an underadditive effect of response time across stimulus onset asynchrony (SOA) for geometric trials and an additive effect for landmark trials, suggesting that geometric information is processed during the first stage of processing, and landmark information during the second.

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Introduction

When an organism is disoriented, it may reorient by encoding its current environment and comparing the encoded representation to a memory of a familiar setting. Reorientation processes can be thought of as an organism establishing a sense of direction when attempting to navigate (Kelly & Spetch, 2001) or attempting to recall the spatial relations between objects in the environment (Mou, McNamara, Valiquette & Rump, 2004). When an organism is attempting to reorient, there are at least two sources of information available. First is the geometric relationship among elements of the environment. For example, the walls of a room are typically rectangular or square; similarly, three objects may correspond to the vertices of a triangle. Thus, an animal storing its food may encode the location of its cache as being under a rock located in the centre of a triangle defined by three trees. Second is landmark, or feature information, derived from the appearance of specific objects in the environment. For example, a squirrel might remember the specific colour and appearance of the rock. Research on this topic has shown that geometry is used across a wide range of species, at all tested stages of maturity. In contrast, the use of landmark information seems to be either a process that is learned or one that develops as humans mature. The important research question is, however, how an organism processes the kinds of information it has, whether landmarks or geometry. Theories of reorientation processing range from modularity (e.g., Carruthers, 2006) to an adaptive integration of information (e.g., Newcombe & Huttenlocher 2006). An understanding of the underlying mechanisms is the important first step behind understanding the entire process of reorientation.

Previous research studying reorientation behaviour has predominantly used physical paradigms (e.g., Gouteux & Spelke, 2001; Mou, McNamara, Valiquette, & Rump, 2004). In these experiments, participants are disoriented in an experimental environment, and asked to locate a previously encoded target. Although some experiments have used virtual environments (e.g., Hartley, Trinkler & Burgess, 2004), the basic paradigm remains the same: A participant is shown a target, disoriented, and then asked to find the target. The dependent variable from these experiments is participants' accuracy for locating the target. From these data, researchers have begun to make conclusions concerning the speed, and modular nature of reorientation processes. This has the salient drawback of using patterns of accuracy to infer such processing details. As well, the time course of the procedures used in these experiments is not experimentally controlled, thereby preventing proper investigation of the speed and order of reorientation processing. The present research introduces a novel paradigm designed to study the stages of processing of landmark and geometry information using the psychological refractory period (PRP) paradigm. This paradigm allows researchers to make inferences regarding stages of processing using response times as the dependant variable. The results of the present experiments suggest that that there are qualitative differences in how landmark and geometry information is processed. It is my belief that this task represents a meaningful contribution to the study of reorientation processing because it provides the first tool to answer questions of the speed and order of geometry and landmark information in reorientation processing.

Below, I first discuss the use of landmark and geometry information in reorientation. Following this review, I discuss theories of processing of landmark and geometry information. I then introduce the psychological refractory period so as to facilitate understanding of the new paradigm that is introduced in the final section of this introduction.

Landmark and Geometry Information in the Reorientation Paradigm

Researchers studying reorientation in animals soon discovered that geometry was much more likely to be used than landmark information. For example, Cheng (1986) first introduced rats to a rectangular environment where each corner was unique in terms of appearance, texture, amount of light, and odor. The room had two long walls and two short walls. As a result, the environment afforded two geometrically identical pairs of corners: From a perspective inside the room, one pair would have the short wall on the left and the long wall on the right, while the other would have the reverse relationship. Importantly, each corner had many other landmark features that could be used to uniquely recognize it. The rats were exposed to a target location with a food source. Cheng then recorded which corners the rats explored after the rats were removed from this environment, disoriented via rotation, and subsequently returned to an identical environment without food. It appeared as though the rats largely ignored all sources of information except the geometric relationship between the short and long walls. This meant that the rats were only finding the target corner approximately half the time, despite the numerous sources of landmark information available to them. This showed that the rats relied heavily on geometry, even though other information in the environment was both available and more informative. Cheng’s findings have subsequently been replicated with a wide range of species (e.g., pigeons: Kelly & Spetch, 2004b; humans: Hermer & Spelke, 1994; fish: Sovrano, Bisazza & Vallortigara, 2003; chicks: Vallortigara, Feruglio, & Sovrano, 2005). Regarding the nature of reorientation processing, Cheng noted the rats’ reliance on geometry and concluded that geometric information must be processed differently than landmarks, during the course of reorientation. These findings were the first to suggest that there may be fundamental differences between the processing of landmark and geometric information.

Research has searched for the variables in reorientation that control the use of geometry in preference to landmarks. For example, researchers have investigated the nature of orienting behaviour in physical environments (Sovrano, Bisazza & Vallortigara, 2003; Learmonth, Nadel, & Newcombe, 2002; Twyman, Friedman, & Spetch, 2007), models of rooms (Gouteux, Vauclair & Thinus-Blanc, 2001), two-dimensional room schematics (Kelly & Spetch, 2004a), virtual rooms in video games (Hartley, Trinkler & Burgess, 2004), and arrays of objects within rooms (Gouteux & Spelke, 2001). Although the exact pattern of data obtained with these different techniques varies, the common finding is that geometric information is still used in all of these situations. For example, Vallortigara, Feruglio, and Sovrano (2005) found that chicks were able to conjoin both geometric and landmark information in reorienting in a large environment but weighted landmark information less than geometry in a small one. Thus, it appears as though size of environment can affect an organism's use of landmark information, while geometric information is used in all conditions.

Results with humans suggest that the use of landmarks develops with age while the use of geometry is present at a very young age. Hermer and Spelke (1994) found that 24-month old children relied on geometry and ignored landmarks. Furthermore, children failed to utilize the landmarks even after having them pointed out and after playing with the landmarks and placing them in the assigned corner. Adults, however, were found to use landmark information. Hupbach and Nadel (2005) replicated the failure to use landmarks with 36-month old children. However, by 48 months, children were found to use landmark more than geometric information. Thus, it is possible that the ability to use geometry is innate in humans and animals (Chiandetti &

Vallortigara, 2008), as it is evident at the youngest ages that researchers have been able to test. The ability to process landmark information, however, appears to develop as people mature.

Hermer-Vazquez, Spelke, and Katsnelson (1999) found evidence that geometric and landmark information are represented differently. They had adult participants engage in verbal shadowing while encoding a test environment. Subjects started shadowing before they entered the environment and continued while an object was hidden, while disorientation occurred, and while recalling where the object was hidden. Under these conditions, subjects searched for the target in the correct corner and its geometric equivalent equally often despite the availability of landmark information that could identify the correct corner. This finding was taken to indicate that geometry is an intrinsic form of spatial encoding in humans that does not require verbal processing and that oral shadowing interferes with humans' ability to use landmark information.

A subsequent experiment by the same authors demonstrated that landmarks could be encoded even with oral shadowing (Hermer-Vazquez et al., 1999). Instead of hiding the target in a corner, it was placed behind one of the four walls while subjects engaged in shadowing. At test, the walls of the enclosure were separated, reassembled as a flat array and presented in front of the subject. The subject then had to identify which wall the target was behind. Subjects had no difficulty identifying which wall section concealed the target in this condition. Since the room had been disassembled into sections, geometric information was not available for encoding at test for solving this task. Consequently, Hermer-Vazquez et al. concluded that landmark information could be encoded during shadowing but that subjects are unable to retrieve or utilize landmark information when geometric information is available.

In sum, the evidence suggests that in reorientation, landmark and geometric information are represented differently and require qualitatively different processes. Geometry is commonly used across species and can be applied in a wide range of situations. In contrast, not all species readily use landmarks, and when they are used, it may be under particular conditions. In humans at least, the use of landmark information seems to develop with age. These considerations are consistent with the characterization of the use of geometric information as more fundamental and phylogenetically primitive and the use of landmark information as a special-purpose adaptation that in humans is mediated by controlled, verbal processing.

The Nature of Landmark and Geometry Information Processing

Although research has begun to demonstrate which types of information organisms use to reorient and the circumstances under which those different sources of information are used, there is no clear understanding at this time of the nature of the processing that is used to reorient. Below are several theories that attempt to address this issue. These theories can be separated into modular and non-modular camps. Both camps allow for landmarks and geometry to be processed differently, as different mental operations are being undertaken to utilize each. Modular theories, however, predict qualitatively different types of processing for geometric and landmark information, in that geometry is processed by a fast and efficient module, and landmarks are not. Non-modular theories, on the other hand, do not require this qualitative processing difference.

Since Ken Cheng's seminal work on reorientation in rats, it has been suggested that there may be fundamental differences in how geometric and feature information are used during reorientation (Cheng, 1986). Specifically, it was suggested that the processing of geometric information might be modular. From this perspective, the mind is thought to contain cognitive structures that are separate from each other and that are responsible for carrying out different tasks. Modularized processes are assumed to be fast, obligatory, and have specific domains for which they are responsible (Fodor, 2000). The relevant structure to the present discussion is a geometric module whose only function is the processing of geometric information in the environment. If this account is correct, then the processing of geometric information should be both fast, obligatory, and as a result, often be preferentially used in reorientation instead of feature information, while the processing of feature information should not demonstrate these properties. Despite researchers' claims regarding the modularity of processes, and the predictions that would follow from modular processing, there is a surprising absence of research that actually examines process in the reorientation task.

Several different modularity theories exist. Some researchers subscribe to a massively modular theory in which all of cognition is comprised of modular processes (Carruthers, 2006), while others believe that the core foundations of cognition are modular and interact with other, non-modular processes (Spelke & Kinzler, 2007). Cosmides and Tooby (1992) argue that if one is to believe in an evolutionary view of cognitive processes, then one must concede the existence of cognitive modules. This argument follows the logic that natural selection must have an object to select and that without cognitive modules, there is no trait for natural selection to operate upon over the course of evolution. From those theories that are not massively modular, the process of reorientation is often thought to be a two-step system. Reorientation is first performed by a geometric module, which makes a mental record of geometric relations in the environment. Second, the record is then entered, along with feature information in a common store to facilitate access to information pertinent to reorientation (Cheng, 1986; Lee, Shusterman, & Spelke, 2006). As a result, geometry is processed quickly and efficiently by a module while landmark information is not, yet both sources of information are ultimately available in one location, though at different times across the course of processing.

In recent years, theories have been developed that challenge the notion of modularized geometric processing. Such nonmodular accounts have been motivated in part by the flexibility that has been observed in people's reorientation. For example, Ratliff and Newcombe (2008) point out that the size of the environment influences the probability that a participant will use feature information to reorient. Specifically, participants in a small environment are likely to utilize the environment's geometric information to reorient, while participants in a large environment are more likely to use feature information. This finding has been presented as being difficult to explain if a geometric module is a fast process that operates quickly and efficiently, prior to landmark processing. If a geometric module serves as a rapid and economic process for reorientation, then there is no reason why the size of the environment should affect whether or not a geometric module is employed to encode the environment.

Further evidence against a geometric module is found in research examining the effects of training and rearing on reorientation behaviour. Twyman, Friedman, and Spetch (2007) gave young participants training in the use of landmarks in a reorientation paradigm. It was found that in as few as four trials, young children, who normally do not appear to use feature information during reorientation, were able to correctly use a landmark to reorient. With respect to the effects of rearing, Brown et al. (2009) found that fish raised in a circular environment did not rely on geometry as much as those raised in a rectangular environment. Although some of these results could be explained on a modular account, they are more naturally predicted by nonmodular views.

An alternative theory to pure geometric modularity was advanced by Cheng (2005). This hybrid theory involves a shape-matching module that is responsible for establishing the organism's heading. Once heading is determined, geometric and feature information is then encoded and added to the shape-matching record in a common memory store. The common store is then accessed during reorientation. As a result, mental structures responsible for reorientation need only rely on one source of information. However, the representations being introduced to the common store are thought to differ. As with the theory of Lee, Shusterman, and Spelke (2006), the processing of geometric information is still thought to be modularized, while that of landmark information is not. This allows for differences in how quickly different types of information are put into the store. As a result, behavioural differences in reorientation behaviour will be produced based upon when the behaviour is made during reorientation processing. That is, if a response is made very early, then there will only be geometric and heading information in the store, whereas landmark information would be present if the response were made later. From this theory, reorientation is thought to be a product of one memory store that is accessed by multiple systems.

A non-modular theory of reorientation that accounts for the apparent processing differences between geometric and landmark information has been developed by Newcombe and Huttenlocher (2006). These researchers propose a single store of information, much like Cheng (2005). However, Newcombe and Huttenlocher suggest that the systems that provide input to this store have their processes improved by the success and frequency of use over time by becoming faster and having their priorities increased. That is, the more a system (i.e., geometric, feature, shape-matching) leads to adaptive behaviour, the faster it becomes, and more weight is given to that process in the future. As a result, the processes that have proven to be the most useful will develop into faster, stronger processes that guide reorientation more than other processes. Through this adaptive combination mechanism, geometry could develop into a process that would produce the results that have been observed in physical reorientation paradigms, without the need to presume modular processing. That is, if geometry proves to be a reliable source of information for reorientation over the course of an organism's life, it will become the fastest and more heavily relied upon reorientation process. This would result in patterns of reorientation behaviour wherein geometry appears to be processed faster, and possibly in exclusion to, feature information (as in the verbal shadowing experiments of Hermer-Vasquez et al, 1999). From an evolutionary perspective, it is plausible that geometry processing could possess this adaptive advantage, since environmental features change with the season, while the geometric relationship between objects remains constant.

A commonality between the modular and adaptive models is that both allow for differences between geometric information processing and landmark information processing. Modular theories suggest a qualitative difference in the nature of the processing mechanisms: that geometry is processed via a module while landmark information is not. Non-modular, adaptive theories suggest a quantitative difference in processing, in that observed differences are predominantly a function of processing speed. The outcome of the present experiments will address whether this difference exists and whether there are differences in the order in which landmark and geometry information are processed.

The PRP Paradigm

The psychological refractory period (PRP) paradigm can be used to experimentally constrain the sequence of processing. This paradigm was used in the current research to infer the order in which geometry and landmark information might be processed, and to note any differences in the stages during which each source is processed in humans.

The PRP paradigm involves two speeded-choice tasks performed in rapid succession, with the stimulus onset asynchrony (SOA) between the two task stimuli varying across trials (Welford, 1952). Subjects are typically instructed to make both responses quickly but to respond to the first stimulus first. Under such conditions, it is generally found that response time for the second task increases as the SOA decreases. This pattern is referred to as the PRP effect.

One of the more common interpretations of the PRP effect is a “bottleneck” model of processing (Pashler, 1994). In this model, processing is divided into early, central, and late stages. Early and late processing for the two tasks can be done in parallel; for example, early perceptual processes may operate on several stimuli at a time, and, under some circumstances, several responses may be executed at the same time. However, the critical feature of this analysis is that central processing can only occur for one task at a time. Thus, central processing of the second task cannot begin until central processing of the first task has been completed. When the second task follows the first at short SOAs, central processing of the second task is likely to be delayed until central processing of the first is completed, leading to longer response times. At longer SOAs, there is less likely to be a delay in Task 2 processing because central processing of the first task will already be complete. Thus, response time for the second task decreases towards an asymptote as SOA is increased. In principle, with a sufficiently long SOA, response time for the second task only reflects how long it takes to complete that task under single-task conditions.

The bottleneck model provides a useful analytical tool because it makes two strong predictions concerning effects of Task 2 difficulty (see Figure 3 for a graphic representation of how these predictions are made). The first is that difficulty manipulations that affect the duration of Task 2 central (or late) processing should be additive with the effect of SOA. That is, Task 2 response times for difficult trials will be longer at all SOAs than for easy trials. This is because central processing of Task 2 must wait for the central processing in Task 1 to be completed. Consequently, any manipulation of the duration of the central (or late) processing for Task 2 will simply add to the effect of SOA. The second prediction of the bottleneck model is that manipulations that affect the duration of Task 2 early processes will have an underadditive interaction with SOA. In particular, Task 2 response times for difficult trials will only be longer at longer SOAs, and there will be little effect of difficulty at the shortest SOAs. When the central bottleneck is occupied with Task 1, it is possible for early processing of Task 2, even when extended due to difficulty manipulations, to be completed while waiting for Task 1 central processing to be completed. Thus, at short SOAs, early processing for Task 2 will occur in parallel with the early or central processing for Task 1. However, at longer SOAs, there is no cognitive slack because Task 1 central processing is completed by the time Task 2 central processing begins. As a consequence, the response times for the second task will reflect the extended early processing as SOA increases. Thus, if the duration of Task 2 early processing varies, the response times for difficult and easy trials at short SOAs should be approximately the same, and the effect of difficulty should be visible only with longer SOAs.

Using this logic, a wide range of research using the PRP paradigm has led to several conclusions concerning the nature of the early, central, and late processing stages. Early processing typically includes perceptual processes such as stimulus identification (Pashler, 1984); the central stage includes capacity-limited processes such as response selection and memory access (e.g., Watter & Logan, 2006); and late processing includes response execution (Pashler, 1994b).

Present Research

In the present research, I conducted two experiments: In Experiment 1, participants used landmark information to complete the task, and in Experiment 2, participants used geometric information to complete the task. An underadditive effect of difficulty and SOA in either experiment would demonstrate that that source of information is processed during early processing, while an additive effect would suggest central processing. Differing patterns of results in the two experiments would speak to the issue of whether there are qualitative differences in the nature of processing for both types of information. By manipulating which source of information participants are able to use, this paradigm should allow for the observation of differences between the processes necessary for each source of information.

In typical versions of the reorientation task, subjects are given a short period of time to encode their surroundings, including the location of a target. They are then disoriented, with their eyes closed, and then told to open their eyes. Thus, subjects, upon opening their eyes, are presented with a novel view of a familiar environment. Logically, I argue that subjects must then encode the available information and compare this representation to their memory of the information that was present in the room at the time of encoding. This comparison is used to identify the location of the target.

I developed a speeded version of the reorientation task that could be used in the PRP paradigm. In this new task, the same sort of information is processed as in the physical reorientation task. In particular, subjects made same/different discriminations of two depictions of a room. The room could be either square (Experiment 1) or rectangular (Experiment 2). A coloured ball was placed in a one corner to play the role of the target in more traditional reorientation paradigms. In geometry conditions of physical reorientation paradigms, the target is typically a corner that is identified during encoding, but is otherwise identical to all other corners in terms of features. In both the traditional and the new paradigms, however, the encoding of the target involves committing to memory one corner's specific feature and/or geometric information for the purpose of later retrieval and comparison. The ball in the present experiment is a clear difference that separates the target corner from other corners. However, I believe that the nature of the encoding to note the ball's location is similar, if not identical to the encoding required in the physical reorientation paradigms. For example, in a square room with a landmark, participants would note a relationship like "to the left of the blue wall" or "across from the right side of the blue wall" in both paradigms. This relationship would need to be kept in mind during disorientation in the physical paradigm, and would need to be kept in mind while encoding the second image in the present paradigm. Thus, in both instances, the nature of the initial processing should be the same.

Pairs of depictions were constructed that differed in viewing perspective by 30˚ to 315˚ (see Figure 1, top right, for a room pair separated by 30˚ and Figure 2, bottom right, for a pair separated by 160˚). This manipulation of viewing perspective corresponds to seeing the room from different perspectives before and after disorientation in the physical reorientation task. The task was to decide whether the two depictions could have come from the same room, given the position of the target. My expectation was that this task would require subjects to process the same type of information that is processed in the physical reorientation task. For example, participants may look at one picture, encode its target's relationship to the geometry or landmark (as appropriate), then look to the second picture and compare its relationships to the mental representation of the first room. This process is analogous to the process described above for physical reorientation paradigms.

The same-different reorientation task I developed was used as Task 2 in the PRP paradigm to explore the processing architecture for landmark and geometry information. The bottleneck account of the PRP effect makes predictions concerning the effect of manipulating Task 2 difficulty. In the present experiments, difficulty was manipulated by varying the amount of rotation between the two room depictions. Small angular disparities between rooms (e.g., 15º) were deemed to be relatively easy and large angular disparities (e.g., 225º) were deemed to be difficult. If this difficulty manipulation affects early processing in Task 2, I would expect to observe underadditive effects of response time and SOA; in contrast, if the difficulty manipulation affects central processing, I would expect to observe an additive interaction of RT and SOA. Thus, I should be able to determine whether each source of information is processed during early or central stages by observing the interaction of SOA and task difficulty in each experiment.

In Experiment 1, the stimuli were arranged so that the same-different task could only be performed using landmark information. The rooms were square, making the use of geometric information impossible, but had one wall coloured blue, providing a landmark (see Figure 1 for an example). There was also the target ball in one corner. Participants needed to compare the target-landmark relationships in the two depictions. For example, if one depiction showed the ball adjacent to the left side of the blue wall, and the other depiction showed the target still on the left side, but opposite the blue wall, subjects would be able to identify this pair as different based on the target's changed relationship to the blue wall. In contrast, the rooms in Experiment 2 were rectangular with an approximately 2:1 aspect ratio. There were no landmarks present, and all walls were the same colour (see Figure 2 for an example). As a result, a same-different judgment required the use of geometric information. For same-room trials, subjects needed to recognize that the target in each picture had the same geometric relationship to the short and long walls, whereas for different-room trials, subjects needed to recognize that the target was not in the same relationship to the room's walls. For example, if one image showed the ball in a corner with the short wall on the right and the long wall on the left, it could be distinguished from a picture showing the ball in a corner with the short wall to the left and the long wall to the right purely on the basis of the room geometry.

I hypothesized that the difficulty of the same/different task would increase with the angular disparity between the perspectives. This predicted effect is comparable to the effect of angular disparity in a mental rotation task (e.g., Shepard & Metzler, 1971). In mental rotation research, subjects are typically presented with two images and asked to make a same/different judgment. A positive linear relationship is observed on same trials between response time and the angular disparity between the two views of the stimulus. Such data are commonly interpreted in terms of a time consuming process of mentally rotating the representation of one object until it matches the other (e.g., Shepard & Metzler, 1971). Ruthruff, Miller, and Lachman (1995) examined mental rotation in the PRP paradigm by using a same/different task with rotated letters as Task 2. They found that response times for rotationally disparate pairs of letters were longer for all SOAs. This suggests that mental rotation requires access to the central bottleneck. As mental rotation is hypothesized to be the strategy that participants will employ to complete the present task, the data from Experiment 1 is expected to show an additive effect of difficulty and SOA, because the difficulty manipulation will affect the add time to the central processing of Task 2.

A pattern of data for Experiment 2 can also be predicted on the basis of previous reorientation experiments. The results from the verbal shadowing paradigm developed by Hermer-Vasquez, Spelke, and Katsnelson (1999) suggest that people are able to encode and use geometric information concurrently with cognitively demanding tasks. This result is consistent with the hypothesis that geometric information is processed prior to a central processing bottleneck. If this were correct, we would expect to see an underadditive effect of SOA and task difficulty in Experiment 2 (see Figure 3 for a diagram).

These experiments stand to be the first examination of reorientation processing using response times rather than accuracy. The results from these experiments will be a contribution to the understanding of the processes responsible for people's reorientation. As well, they will serve as evidence towards the modularity debate by providing a tool for direct testing of some of the predictions of modular processing.

Experiment 1

In Experiment 1, I examined subjects' ability to use landmark information in my speeded version of the reorientation task. Task 1 was a tone discrimination task. This task was selected because the stimuli are unlikely to interfere with the visual stimuli presented in the reorientation task. Stimuli for the reorientation task depicted square rooms with one wall coloured blue. Because a square room provides no geometric information, subjects would have to rely on landmark information to perform the task. A priori, I presume that participants will perform the room task in this experiment using a process akin to mental rotation. As a result, I conjecture that subjects process landmark information during central processing (as in Ruthruff, Miller, & Lachman, 1995). If so, the effects of difficulty and SOA should be additive, as demonstrated in experiments testing mental rotation in a PRP paradigm.

Method

Subjects. Twenty undergraduate students from the University of Alberta participated in this study for course credit. Data from three subjects were not used because of error rates on Task 2 greater than 15%.

Apparatus and Stimuli. The sound stimuli used for Task 1 (a beep and a tap) were downloaded from The Free Sound Project (Free Sound Project, 2008a; Free Sound Project, 2008b). Both sounds were trimmed to a duration of 15 ms and presented at comfortable listening volume over the computer speakers.

The graphic stimuli for Task 2 were generated by using the program Blender (Blender Foundation, 2008) to design virtual rooms and then render two-dimensional views of the rooms from different angles (e.g., Figure 4). The virtual rooms were designed to be 8.1 m along each wall. On the screen, the images were sized 22.5 cm x 16.5 cm. The ceiling and three walls were coloured white, but one wall was coloured bright blue (corresponding to RGB values of (1, 158, 211) in the Mac OS X colour space). The floors were patterned with a 9 x 9 black and white checkered pattern with what would be 90 cm x 90 cm squares. A red sphere with a diameter of 90 cm was used as the target. The target was positioned in a corner, in one of four possible relationships to the landmark (blue wall): The ball could be in a corner adjacent to and left of the landmark, adjacent to and right of the landmark, left and opposite the landmark, and right and opposite the landmark.

Individual views were rendered by placing the rendering “camera” outside of the room, halfway between the floor and ceiling and pointed towards the centre of the room. The two near walls were not drawn so that the rendered scene depicted the target and its position relative to the landmark. As shown in Figure 4, eight possible viewing angles were selected by first bisecting the room corner-to-corner and wall midpoint-to-midpoint, and then selecting an orientation that was halfway between the corner and wall bisectors. The angles thus spanned different possible perspectives on the room while avoiding alignment with the walls or the diagonals. This resulted in camera pointing the center of the room at rotations of 22º, 68º, 112º, 158º, 202º, 248º, 292º, and 338º. The camera distance was then selected so that the most eccentric scene edge coincided with the limit of the camera's field of view. These distances ranged from 10 m-12.5 m from the center of the room. The two camera angles in which the target occupied the near corner were not used, leaving six possible viewing angles for each of the four target positions.

Stimuli consisted of pairs of renderings that were either of the same room or of two rooms with different target positions. The two same-room depictions ranged from one to seven steps apart, thereby ensuring that the two images were not identical. Different-room pairs were selected so that the amount of rotation necessary to align the targets in the two depictions was a comparable number of steps apart as the same-room pairs. However, the target had a different relationship to the coloured wall in the two depictions. With the constraints listed above, 16 pairs of same-room renderings were possible. As the room was square, the angular disparity between the views of the two rooms was 45º, 90º, 135º, 180º, 225º, 270º, or 315º. The 45º and 315º pairs were coded as easy because of their low angular disparity, as both are only 45º apart. The 180º pairs were also coded as easy because they could be solved with a simple rule, rather than performing mental rotation. That is, at 180º, the two images will be indistinguishable except for the position of the ball. As a result, participants need not engage in rotation, and can simply recognize same and different pairs by attending purely to the ball. All other angular disparities were coded as difficult. This classification resulted in 4 difficult same pairs, 6 difficult different pairs, 12 easy same pairs, and 10 easy different pairs. A complete list of stimuli appears in Table 1.

Participants were seated approximately 60 cm from a 43 cm LCD computer monitor with a resolution of 72 dpi. At that distance, the combined display subtended approximately 9^{o} of visual angle vertically and 9.5^{o} of visual angle horizontally. Both images were presented simultaneously, one above the other, separated by 14 cm center-to-center, with both pictures centered horizontally.

Procedure.

After reading and signing an informed-consent form, participants were given ten practice trials. Once the practice trials were complete, subjects were left alone to complete three test blocks of 100 trials each. Each block was separated by a break. The stimuli on each trial were selected randomly with replacement.

Each trial began with the word “READY” presented in the centre of the screen. Subjects initiated the trial by pressing the space bar. After a 500 ms delay, one of the two sounds was presented. Subjects were asked to identify the sound by pressing the Q key (for a tone) with their left middle finger or the A key (for a tap) with their left index finger. The room stimuli were presented after a randomly selected SOA of 100, 200, 300, 500, 700, or 1000 ms. A pair of rooms was then presented in the centre of the screen. Subjects indicated whether the rooms were the same or different by pressing the 1 key or the 3 key respectively on the numeric keypad with their right index finger.

Analysis

The data were analyzed by fitting nested linear models (for response times) and generalized linear models (for accuracy) and comparing the models using likelihood ratios. The models were fit using mixed-effects analysis using the R program lmer from the lme4 package (Bates, Maechler, & Dai, 2008; R Development Core Team, 2008). In mixed-effects modeling, one specifies which factors are random and which are fixed, and the program uses a search algorithm to find maximum likelihood estimates of the model parameters. In the present experiment, subjects were used as a random effect. Pairs of models were compared by computing the likelihood ratio. The likelihood ratio indicates the likelihood of the data given the fit of one model relative to the likelihood of the data given the best fit of another and provides an intuitive assessment of the relative quality of the two fits. Following the suggestion of Glover and Dixon (2004), the likelihood ratios were adjusted for the differing degrees of freedom in the models based on the Akaike Information Criterion (Akaike, 1971). I will refer to this statistic as λ_{adj}. By way of comparison, in some prototypical hypothesis testing situations, a statistically significant effect corresponds to an adjusted likelihood ratio of about 3. The effect of SOA was modeled with quadratic and linear trends. These two trends suffice to model the general form of PRP effects in which response time decreases rapidly over short SOAs and reaches an asymptote at long SOAs.

Analysis of response times was constrained to those trials on which both tasks were performed correctly. Accuracy for the sound task was 98.7%. Accuracy for the room task was 90.8%. All trials that had response times in excess of 10 seconds on the room task were also discarded as outliers (an additional 2.3%). All told, 88.7% of the data were included in the analysis.

Results

The mean response times for the speeded reorientation task are shown in Figure 5 as a function of difficulty and SOA. There are three critical aspects of the results. First, response time on difficult trials was slower than on easy trials. Second, response time decreased with increasing SOA as typically found in the PRP paradigm. Third, the effects of difficulty and SOA were additive.

To assess the evidence for this interpretation, I compared the fit of four nested linear models. First, I compared a model that included only difficulty to a null model with no effects. The difficulty model was better ($\lambda_{adj} > 1000$). Second, I compared the difficulty model to a model with an added overall effect of SOA. The difficulty-plus-SOA model was superior ($\lambda_{adj} > 1000$). Finally, this additive model was compared with one that allowed for an interaction between difficulty and SOA. The interaction model was worse ($\lambda_{adj} = 0.10$), indicating good evidence in favour of the additive model ($\lambda_{adj} = 9.91$).

The patterns of means for same and different trials were not the same (see Table 2). Specifically, there was a clear effect of task difficulty in the same-room condition but no such effect in the different-room condition. Evidence for this interaction was obtained by comparing the best model, presented above, with a model in which the effect of difficulty was limited to the same-room condition, as well as an overall effect of type of room pair. The new model was superior ($\lambda_{adj} > 1000$). The previous model was compared to a full model that included all possible interactions. The full model was worse ($\lambda_{adj} = 0.26$), suggesting that there were no important interactions with SOA.

Response times for the first, tone task were unaffected by any of the room task difficulty manipulations. A null model for the tone task response times was compared to a model with an effect of SOA ($\lambda_{adj} = .476$), a model with an effect of difficulty ($\lambda_{adj} = 0.51$), and a model with an interaction between SOA and difficulty ($\lambda_{adj} =0.10$), providing no evidence for an alternative to the null model. A summary of Task 1 response times as a function of SOA and task difficulty can be found in Table 3.

An analysis of the room task error rates showed an effect of difficulty and same/different room pairs but not SOA. A null model of Task 2 accuracy was compared to one with an effect of SOA. The SOA model was worse ($\lambda_{adj} = 0.18$), providing good evidence for a model that does not include SOA. Next, the null model was compared to one that allowed for an effect of task difficulty. The model with task difficulty was better ($\lambda_{adj} > 1000$). This is consistent with the prediction that a process akin to mental rotation was used in the room task because mental rotation is likely to be a comparatively error-prone process. The task-difficulty model was then compared to one with an effect of same/different to test the differential effect of difficulty across same and different trials effect evident in Figure 6. It is clear that there was a stronger effect of task difficulty in the Same trials than in the Different trials. A model in which the effect of difficulty was limited to same-room pairs was better ($\lambda_{adj} > 1000$). Finally, the model with effects of same/different and difficulty was compared to a model that included an interaction. The interaction model was superior ($\lambda_{adj} > 1000$).

Discussion

The key finding from Experiment 1 was the additive effects of difficulty and SOA on Task 2 response times. This pattern suggests that the difficulty manipulation affected processing that occurs either during or after the bottleneck. This is consistent with Ruthruff, Miller, and Lachman's (1995) research that showed that mental rotation occurred during the central processing stage. Thus, it seems plausible to suppose that subjects were employing a process akin to mental rotation to complete Task 2 in this experiment.

The data from this experiment are also consistent with the idea that the processing of landmark information occurs during or after central processing, and thereby produces a bottleneck if multiple tasks are being completed concurrently that require central processing. This conclusion is supported by the additive effects of the difficulty manipulation and SOA, as shown by the results in Figure 5. This suggests that subjects were employing the predicted strategy of mental rotation to complete the second task.

Experiment 2

In Experiment 2, I examined the use of geometric information in performing the room task. Room depictions were of rectangular rooms with no distinguishable landmarks. As a result, target location was purely a function of target-geometry relationships. If geometric relationships can be processed prior to the central bottleneck, then the difficulty produced by varying the disparity between two room views should produce an underadditive interaction with SOA. This would occur for all trials because early processing in Task 2 can occur concurrently with Task 1 central processing, and there would be little effect of Task 2 difficulty at short SOAs.

Method

Subjects. Twenty undergraduate students from the University of Alberta participated in this study for course credit. Data from four subjects were not used because of error rates in the room task of greater than 15%.

Apparatus and Stimuli. The sound stimuli used for Task 1 were the same as in Experiment 1.

As before, Blender was used to create the rooms for this experiment and to render the two-dimensional pictures (Blender Foundation, 2008). The rooms for Experiment 2 were comparable to those used in Experiment 1 except that the room was rectangular. The virtual rooms were designed to depict a room with the measurements: 15.3 m long, 8.1 m wide, and 2.5 m tall. The ceiling and all walls were coloured white to eliminate landmark information. An example is presented in Figure 2. A 9 x 17 checkerboard pattern of 90 cm squares was used on the floor, similar to Experiment 1, and the target was the same as well. The constraint that the target could not be in the corner nearest the rendering camera was also used in generating stimuli for this experiment.

As in Experiment 1, camera orientations were selected that were halfway between wall bisectors and corner bisectors, and distances were selected to so that the most eccentric scene edge was at the edge of the field of view. However, because of the different room dimensions used here, the camera orientations were 13º, 43º, 133º, 167º, 193º, 223º, 317º, and 347º.

Stimuli consisted of pairs of renderings that were either of the same room or of two rooms with different target positions. The two depictions were either two or four steps apart to control minimum and maximum rotational differences given that there were fewer constraints on stimulus generation than in Experiment 1 (e.g., 13º and 133º, 43º and 233º). Because the two views in which the target was in the near corner were not used, there were four possible pairs that were two steps apart and two possible pairs that were four steps apart, for a total of six pairs of views of each room. Thus, there were a total of twelve same-room pairs, six for each of the two possible target locations. Different-room pairs were constructed so as to ensure that each pair shared the same number of rotational steps of a same-room pair based on the location of the target. These numbers are different than those in Experiment 1 due to the fact that the room images in Experiment 2 were not constructed with the constraint that a landmark had to be visible in all images. As a result, there were more stimuli options for Experiment 2. A complete list of the stimuli used appears in Table 4.

Trials were coded as being easy or difficult as a function of the amount of rotation necessary for the target in the upper picture to be aligned with that in the lower. As in Experiment 1, stimuli were coded as easy when the angular disparity between the room perspectives was less than 50º or exactly 180º; all other pairs were coded as difficult. When the two stimuli depicted rooms 180º apart, the task was straightforward because the only difference in the depictions was in the target location. This classification yielded 3 difficult same pairs, 9 difficult different pairs, 9 easy same pairs, and 3 easy different pairs.

Procedure. The procedure was the same as that used in Experiment 1.

Analysis. Mean accuracy for the room task was 93.9% (standard error, calculated across subjects 0.02%). Mean accuracy for the sound task was 98.1% (standard error 0.01%). Trials on which either response was incorrect were excluded in the analysis of response times. All trials exceeding a response time of ten seconds on the room task were also discarded (2.33%). All told, 84.6% of the data were included in the analyses.

Data were analyzed using the same model comparison methods outlined in Experiment 1.

Results

Mean response time for the room task is shown in Figure 7 as a function of difficulty and SOA. There are three critical aspects of the results. First, response times were slower to difficult trials than to easy trials, confirming my distinction based on the angular disparity between the views. Second, there was an overall decrease in response time with increasing SOA, consistent with previous research using the PRP paradigm. And third, there was an underadditive interaction between SOA and difficulty, such that the difficulty effect was minimal at short SOAs and substantially larger for longer SOAs.

To assess the evidence for this interpretation, I compared the fit of four nested linear models. First, I compared the fit of a model that included only an effect of difficulty to a null model that included no effects. The difficulty model was substantially better ($\lambda_{adj} > 1000$). Second, I compared the difficulty model to a model that also included an overall effect of SOA, coded as linear and quadratic trends. Again, the model that incorporated both the effect of SOA and difficulty was superior ($\lambda_{adj} >1000$). Finally, I compared this additive model to one that also included an interaction between the SOA trends and difficulty. This interaction model was substantially better ($\lambda_{adj} >1000$), providing strong evidence for the underadditive interaction apparent in Figure 7.

Response times are broken down by same/different response in Table 5. There was little apparent difference between subjects' performance on same and different trials. As a result, the best model was contrasted with a model that also included the factor of same/different trial as well as all possible interactions. This comparison favoured the simpler model ($\lambda_{adj} =0.03$). This suggests that there were no important effects or interactions with room-pair type.

As in Experiment 1, response times for the first, tone task were unaffected by any of the room task difficulty manipulations. A null model for the tone task response times was compared to a model with an effect of SOA ($\lambda_{adj} = .25$), a model with an effect of difficulty ($\lambda_{adj} = 0.61$), and a model with an interaction between SOA and difficulty ($\lambda_{adj} =0.18$), providing no evidence for an alternative to the null model. A summary of Task 1 response times as a function of SOA and task difficulty can be found in Table 6.

Error rates on the room task decreased (see Table 7). The null model was compared to a model allowing for an effect of SOA. The SOA model was better ($\lambda_{adj} = 5.10$). The model with an effect of SOA was then compared to a model that included an effect of Task 2 difficulty. The latter model was better ($\lambda_{adj} > 1000$). When this model was contrasted with a model that included an interaction of Task 2 difficulty and SOA, the interaction model was found to be better ($\lambda_{adj} > 1000$). When the model with the interaction of SOA and Task 2 difficulty was contrasted to a model that included whether subjects were completing a same or different trial, it was found that the latter model was worse ($\lambda_{adj} = 0.05$).

Discussion

The data from this experiment demonstrate an underadditive interaction between difficulty and SOA. This pattern suggests that subjects were able to complete the part of the room comparison affected by the difficulty manipulation during early processing, prior to the central bottleneck. If subjects were engaging in a process that required access to the central bottleneck, such as mental rotation, there should have been an additive effect of difficulty and SOA overall, as found in Experiment 1. This suggests that there is something about target-geometry relationships that permits processing to occur without engaging in the same type of strategies for solving this type of task as is required by target-landmark relationships. However, this alternative strategy was still affected by the task difficulty. That is, even though the subjects were apparently able to employ a strategy other than mental rotation, the amount of angular disparity still affected subjects' response times to the second task (see Figure 8). A model addressing this, involving allocentric referent axes, is presented in the General Discussion.

General Discussion

The results of Experiments 1 and 2 support the view that there are differences between how landmark and geometric information are processed. Specifically, the additive effect found in Experiment 1 suggests that the processing of landmark information occurs during, or after the central cognitive bottleneck. In contrast, the underadditive effect in the Experiment 2 provides evidence that geometric relations can be processed prior to the central bottleneck. This pattern of evidence is congruent with the predictions generated from the physical-reorientation experiments. In such experiments, people have been shown to rely on geometric information when simultaneously disoriented and engaged in cognitively demanding oral shadowing. Thus, the pattern of results produced in the present experiment serves to both support present theories of reorientation processes and illuminate the nature of those processes.

The data, thus far, have been explained using a bottleneck model of the psychological refractory period. The bottleneck model provides a simple framework that explains a wide range of phenomena in this paradigm. There are, however, several alternative interpretations of the results from PRP tasks. These interpretations differ in the presumed nature of the underlying mechanisms that produce the PRP effect. However, regardless of the perspective to which subscribes, the same pattern of results for Task 2 response times given manipulations of Task 2 difficulty is predicted.

One alternative explanation has been developed by Meyer and Kieras (1997a) that is a detailed model of cognitive processing that describes the PRP effect differently than the bottleneck model. Foremost, they argued that the observed processing bottleneck is strategic in nature and that all of the processing of the second task could theoretically be completed in parallel with that of the first task under some circumstances. The typical PRP requirement to produce a response to the first task prior to making one to the second task leads to a strategic manipulation of the scheduling of both tasks' processing components. Meyer and Kieras's model centers around a detailed quantitative analysis of the processing operations and how they can be scheduled to maintain response order. They estimate the time for operations such as focusing one's eyes to on and recognizing a stimulus, selecting a response to either task, and starting and stopping the processing of the different tasks. Given any particular set of these parameters, and the specific inequality required by the order of responses, one of five different processing paths is used to complete the tasks in a PRP trial. They used computer simulation to demonstrate that common effects found in the PRP paradigm can be predicted in this way.

Meyer and Kieras's model explains the classic PRP pattern of response times through a central executive that assigns "stop points" for both tasks in order to control task scheduling. These stop points are functionally equivalent to processing bottlenecks in that they can introduce cognitive slack into task processing by forcing the processing for one task to wait for the processing for the other task to reach a certain point. These stop points serve to create the typical PRP effects through the time it takes for them to be 'unlocked' once they have been put in place. As a result, if processing of the second task reaches its stop point before Task 1 is sufficiently complete, Task 2 is deferred until processing of the first task is far enough along that response order will conform to task demands. There is then a delay while the central executive recognizes that Task 1 is complete, and undergoes the process of unlocking Task 2 processing. The PRP effect is produced as a function of how much processing of Task 1 is completed before Task 2 is presented, and when the unlocking delay takes place, as there will be no special restrictions put on Task 1 processing until Task 2 is presented. If Task 1 is complete or nearly complete (as it would be with long SOAs), then there will be no need to add stop points to Task 2 processing, and response time will be short because there is no unlocking delay. However, at short SOAs, Task 1 and Task 2 will be processed concurrently. This can potentially lead to a stop point being reached during Task 2's processing. This stop point delays processing, as per task demands, and results in extended response times. That is, the stop points are placed strategically so as to maximize one's performance while also adhering to the task demands that the first task be completed first. So long as Task 1 is undergoing processing, Task 2 stands to have stop-points placed to limit its processing to ensure that it does not complete before Task 1. This stop point would be placed once it became apparent that task demands (finish Task 1 before Task 2) were not going to be met. Despite the difference in suggested processes, this is an equivalent process to that proposed by the bottleneck model. That is, in both cases, Task 2 is made to wait for the completion of Task 1. If the data of the present experiment were to be framed in this model, the predictions would remain the same, but the results would be interpreted as a function of strategic processing stop points rather than a predictable order of ballistic processing. Although the specifics of this model are too specific for this review, the key component is essentially the amount of processing that has been done on Task 2 before the participant is ready to make a response to Task 1.

Another alternative is Tombu and Jolicouer's (2003) capacity-sharing model of the PRP effect. In this model, there is no all-or-nothing central bottleneck that limits task processing, and several central processes can be done in parallel. Despite this difference, this model's predictions for Task 2 response times are similar to those of the bottleneck model. Rather, the key differences between the models are in how the nature of processing is conceived and how Task 1 response times are affected by SOA and Task 2 difficulty. In the capacity-sharing model, there are finite cognitive resources that can be allocated to concurrent central processing.

Although this implies that tasks, in principle, can be done in parallel, the PRP effect is caused by task demands. Due to the requirement that Task 1 be completed before Task 2, Task 1 receives a higher priority and thus more processing resources. The PRP effect is therefore driven by the amount of time the two tasks must share central resources. At longer SOAs, Task 1 is processed without competition for a longer period of time and consequently does not require as much sharing of central resources once Task 2 is presented. As a result, both tasks are completed faster because the tasks do not share resources to the same degree as they would at shorter SOAs. As SOA is reduced, however, central processing for the two tasks overlaps, and the tasks must share resources. Potentially, both Task 1 and Task 2 may suffer. However, because of the higher priority given to Task 1, Task 2 will suffer most of the delay. This produces a PRP effect much as the central bottleneck would, but predicts that Task 1 will be slowed somewhat at short SOAs as well.

In a typical PRP paradigm, such as that employed in this research, all three of these models make the same predictions for Task 2 response times. Tombu and Jolicoeur's resource sharing model's predictions deviate from those of the bottleneck model solely with respect to performance on Task 1 (Tombu & Jolicoeur, 2002). For example, if early processing is difficult in Task 2, Tombu and Jolicoeur propose that it will require more of the shared resources to be completed. The response time benefit gained by the extra resource allocation will produce the predicted underadditive effect, much as if the early processing was being completed during cognitive slack. Meyer and Kieras's processing model specifies that the PRP pattern is created due to task demands, and that tasks can be done in parallel. If the difficulty of Task 2 takes place early in processing, the central mechanisms will recognize that it is not likely to complete processing before Task 1 processing is complete, and as a result, not place a stop point to hinder

Task 2 processing. As both tasks are able to run in parallel, difficult early processing in this model will also produce the predicted underadditive effect. Given that the present research employed typical PRP paradigm task demands, we can expect the results to reflect the classic PRP results regardless of which model is used to explain the underlying processes.

Although there are clear differences between physical reorientation paradigms and the present speeded reorientation task, the present research provides evidence concerning the stages of processing involved in processing landmarks and geometry. However, the new paradigm developed here is comparable to physical reorientation in terms of the information required to complete each task. In both a physical, rectangular, featureless room and the rectangular room stimuli used in Experiment 2, subjects must process and compare geometric information and representations. As a result, even though my speeded task cannot speak directly to the process of physical reorientation, it can definitely help describe how landmark and geometric information are processed. In the verbal shadowing experiments presented earlier, for example, it was shown that there were situations where people processed geometric but not landmark information. Although it cannot be said that the current research and the verbal shadowing studies tested the same processes, both experiments' data suggest that there are different types of processing required for geometric and landmark information.

The present data also speaks to the processing that subjects perform in physical reorientation paradigms. In physical-reorientation paradigms, subjects are asked to close their eyes, undergo disorientation, and then are instructed to open their eyes. I hypothesize that the type of processing that follows disorientation is comparable to that which occurs in the present paradigm when subjects are presented with two images of a room and asked to make same/different decisions. In both situations, people must first encode and create a mental representation of an environment and its landmark or geometric relationships. In physical world tasks, this initial environment is the room as it is during encoding, and, in the present paradigm, it is whichever image is processed first. In both situations, people must next compare their representation with their new view of the environment. In the physical world paradigm, this is whichever viewpoint is visible after disorientation, and, in the current paradigm, it is the second image to be processed. One critical difference between the two paradigms is that memory for the first representation is much less critical in the current speeded version because both rooms are perceptually available throughout the trial. This is likely to limit the participants' processing to landmark and feature information, without any possible interference or interaction of a heavy working memory load. Although there is no evidence directly linking the present paradigm to physical reorientation paradigms, the congruency between both bodies of research supports the present suggestion that the present paradigm is a useful tool to examine the course of processing for how people compare landmark and geometric information.

A priori, it is plausible to suppose that the same/different task could be accomplished using a process akin to mental rotation. For example, in Experiment 1, subjects may first have encoded the top view and created a mental representation of the heading of the target and landmark, as well as the relative direction from which the stimuli were encoded. Second, they would look at the lower image noting the same positions, relationships, and heading. The first representation would then be rotated incrementally until the two headings aligned. One of these represented relationships would then be mentally rotated incrementally until the two headings aligned. Once this was complete, a same/different decision could be made by comparing the target-landmark relationships in each image. The additive effect found in Experiment 1 is consistent with research on mental rotation in the PRP paradigm that suggests that mental rotation requires the central bottleneck.

In contrast, the underadditive interaction in Experiment 2 suggests that a central process was not used, which in turn suggests that the comparison process did not involve mental rotations. Instead, I hypothesize that the same/different task in Experiment 2 was performed by making left/right discriminations with respect to the room axis. In order to complete the reorientation task, the subjects in Experiment 2 may have viewed the first room image, established an allocentric referent direction parallel to the long axis of the room, and encoded whether the target was left or right of this axis. Then, subjects would perform the same process with the second image. If the room views are encoded in this fashion, subjects need only decide whether both targets are on the same side of the axis in order to make a same/different decision. Mental rotation and other central processes might not be needed for such a comparison.

As described, this comparison would be unaffected by the angular disparity between the views. This process would, however, produce an effect of difficulty in some situations. For example, if one were to apply the process proposed above to the stimuli in Figure 2, bottom left, one would produce an answer of “right” for both the top and bottom images, and this would lead to an incorrect “same” decision in the present paradigm. Instead, a subject must recognize that the target in the bottom image is adjacent to the near walls of the room, while the target in the top image is adjacent to the far walls. Under such circumstances, the left/right rule must be reversed. To solve this problem, the process would have to be enhanced. Specifically, subjects would first encode the targets’ left/right relationship to the room’s long axis, compare this relationship between the two stimuli, and create a mental index with a result of “same” or “different.” Next, participants would compare whether the target was far or near in each image.

If they are the same, the original index is used. If they are different, then the original index is reversed before a response is made. It is this additional comparison and rule adjustment stage that would produce an effect of difficulty on some trials in Experiment 2.

The hypothesis that people use room axes to encode their environment is not a new one. Shelton and McNamara (1997) showed that people normally will establish egocentric referent directions in order to encode the location of target objects. In Shelton and McNamara's experiments, subjects were presented with an array of objects on a table and were later asked to make same/different decisions regarding arrays depicted from various viewpoints. Subjects were found to be better at the task when the picture portrayed the array from the learned viewpoint. The long axis of the room in Experiment 2 offers an allocentric referent direction which subjects have been found to use to learn environments (Mou, Fan, McNamara, & Owen, 2008). When learning arrays of objects on a table, subjects have been found to better make same/different decisions about the presented objects if the arrays are presented in accordance to a learned allocentric viewpoint, irrespective of their egocentric viewpoint (Mou et al., 2004). This implies that people can look at a scene and encode its features according to patterns other than that provided their egocentric perspective. When comparing the two images in the room task, subjects would then simply need to establish the same long-wall axis in the second image and make a decision regarding whether the target shared the same left/right relationship to the axis as presented in the first image. This process would conceivably not require access to the central bottleneck and would therefore produce an underadditive effect when employed in the PRP paradigm. If this were found to be true, then researchers would have a concrete starting point for further examinations of landmark and geometry processing.

Conclusions

The present research provides several conclusions concerning reorientation. First, the data support the view that there are separate cognitive processes responsible for the processing of geometric and landmark information. Second, when a person needs to reorient, I conclude that geometry is encoded and compared during early stages of processing. This implies that organisms will be able to process similarities and differences between their mental representation of the environment and their present surroundings concurrently with other cognitively demanding tasks. The processing of landmark information requires central resources, possibly due to its reliance on mental rotation.

A specific order of information processing has been demonstrated here that has not otherwise been suggested in the literature. This order exists due to geometric information being processed during early processing, parallel to other processes, while landmark information is processed later, during central processing, and is subject to being queued in a bottleneck if other processes must be completed first. These data are a new addition to reorientation literature and fit nicely with previous research that has suggested a difference between how geometric and landmark information is processed (i.e., Cheng, 1986; Hermer-Vazquez, Spelke, & Katsnelson, 1999). Specifically, the present results speak directly to the order in which the two sources of information are processed. As well, the processing of landmark and geometry information has been shown be qualitatively different in that geometry processing can be completed before the central bottleneck, and concurrently with other tasks, while landmark information requires the central bottleneck.

The present data stand to provide evidence for modular processing of geometry. The different pattern of data found between Experiments 1 and 2 suggest that there is a fundamental difference in how landmark and geometric information is processed. The primary difference between the experiments is not one of response time, but one of underadditivity and additivity, suggesting that each type of information is processed during a different stage of processing. This pattern of data fits more readily with modular theories than with non-modular theories.

Finally, the present data serve to address the lack of research addressing the actual process of using geometric and feature information. The paradigm introduced in this paper allows researchers to begin asking specific questions of the differences and order of landmark and geometry processing rather than relying on accuracy data to infer the nature of processing. Researchers engaged in the modularity debate of geometric processing can now directly test their theories concerning their predictions of the qualities of a modularized process.

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Table 1

Table 1

List of Stimuli used in Experiment 1

	Top Image			*Bottom Image*		
Condition	*Rotation*	*Wall*	*Target*	*Rotation*	*Wall*	*Target*
Same	-22	Left	Center	22	Right	Right
Same	-22	Left	Left	22	Right	Center
Same	-68	Left	Center	-22	Left	Center
Same	-68	Left	Left	-22	Left	Left
Same	22	Right	Center	68	Right	Center
Same	22	Right	Right	68	Right	Right
Same	-68	Left	Center	68	Right	Right
Same	-68	Left	Left	68	Right	Center
Same	68	Right	Center	-68	Left	Left
Same	68	Right	Right	-68	Left	Center
Same	-22	Left	Center	-68	Left	Center
Same	-22	Left	Left	-68	Left	Left
Same	68	Right	Center	22	Right	Center
Same	68	Right	Right	22	Right	Right
Same	22	Right	Center	-22	Left	Left
Same	22	Right	Right	-22	Left	Center
Different	-22	Left	Center	22	Right	Center
Different	-68	Left	Center	-22	Left	Left
Different	22	Right	Center	68	Right	Right
Different	-68	Left	Left	-22	Left	Center
Different	22	Right	Right	68	Right	Center
Different	-22	Left	Left	68	Right	Right
Different	-68	Left	Left	22	Right	Right
Different	-68	Left	Center	68	Right	Center
Different	68	Right	Center	-68	Left	Center
Different	68	Right	Right	-22	Left	Left
Different	22	Right	Right	-68	Left	Left
Different	-22	Left	Center	-68	Left	Left
Different	-22	Left	Left	-68	Left	Center
Different	-22	Right	Center	22	Right	Right
Different	68	Right	Right	22	Right	Center
Different	22	Right	Center	-22	Left	Center

All rotations are presented from the viewer's perspective, with clockwise rotation presented as positive values and counterclockwise rotation presented as negative values. 'Wall' denotes whether the landmark was the left or right visible wall. 'Target' denotes whether the ball was in the left, right, or central corner visible to the viewer, as described in the methods section.

Table 2

Room Task Response Time (and standard error) in ms. as a Function of Task Difficulty and Response in Experiment 1

Response	*Difficulty*	*Stimulus Onset Asynchrony (ms)*					
		100	200	300	500	700	1000
Same	Easy	2315 (78)	2246 (67)	2187 (79)	2086 (78)	1951 (71)	1916 (72)
	Hard	2705 (156)	2438 (146)	2595 (147)	2642 (147)	2567 (147)	2666 (187)
Different	Easy	2768 (95)	2611 (88)	2549 (90)	2589 (97)	2335 (79)	2317 (98)
	Hard	2999 (125)	2531 (122)	2549 (143)	2547 (118)	2391 (100)	2365 (115)

Standard errors were computed by combining estimates of the relevant parameters in a full mixed effect model, excluding variability attributed to the intercept.

Table 3

Mean Task 1 Response Time (and standard error) in ms. as a Function of Task Difficulty and SOA in Experiment 1

Difficulty	*SOA*					
	100	200	300	500	700	1000
Easy	2465 (11)	2349 (7)	2332 (11)	2247 (12)	2144 (7)	2033 (11)
Hard	2945 (11)	2582 (7)	2604 (11)	2453 (12)	2496 (7)	2442 (11)

Standard errors were computed by taking the standard error of the difference scores between subjects' response times on easy and hard trials.

Table 4
List of Stimuli used in Experiment 2

	Top Image		*Bottom Image*	
Condition	*Rotation*	*Target*	*Rotation*	*Target*
Same	-13	Center	43	Right
Same	13	Left	-43	Center
Same	13	Left	13	Right
Same	-43	Center	13	Right
Same	43	Left	-13	Center
Same	43	Left	43	Right
Same	-13	Right	43	Center
Same	-13	Right	-13	Left
Same	13	Center	-43	Left
Same	-43	Right	-43	Left
Same	-43	Right	13	Center
Same	43	Center	-13	Left
Different	-43	Right	43	Right
Different	43	Left	-13	Left
Different	13	Left	-13	Right
Different	13	Left	43	Center
Different	-43	Center	-13	Left
Different	43	Left	-43	Left
Different	43	Left	13	Center
Different	-13	Right	-43	Center
Different	-13	Right	13	Right
Different	13	Center	43	Right
Different	-43	Right	-13	Center
Different	43	Center	13	Right

All rotations are presented from the viewer's perspective, with clockwise rotation presented as positive values and counterclockwise rotation presented as negative values. 'Target' denotes whether the ball was in the left, right, or central corner visible to the viewer, as described in the methods section.

Table 5

Mean Task 2 Response Time (and Standard Error) as a Function of Easy and Hard Same/Different Trials in Experiment 2

Condition	*Difficulty*	*SOA*					
		100	200	300	500	700	1000
Same	Easy	2732 (90)	2719 (95)	2479 (86)	2516 (94)	2552 (98)	2519 (95)
	Hard	2744 (153)	2829 (160)	2715 (137)	2723 (153)	2798 (178)	2659 (147)
Different	Easy	2639 (170)	2501 (147)	2637 (177)	3178 (125)	2017 (144)	2033 (122)
	Hard	2936 (95)	3008 (94)	2867 (93)	2759 (96)	2673 (96)	2649 (88)

Standard errors, were computed by combining estimates of the relevant parameters in a full mixed effect model, excluding variability attributed to the intercept.

Table 6

Mean Task 2 Percent Accuracy (and Standard Error) as a Function of Easy and Hard Same/Different Trials in Experiment 1

Condition	*Difficulty*	*SOA*					
		100	200	300	500	700	1000
Same	Easy	94.6 (5.0)	93.8 (5.0)	93.8 (3.8)	93.0 (6.9)	95.5 (4.6)	92.3 (5.7)
	Hard	91.2 (5.0)	88.8 (5.0)	92.5 (3.8)	91.0(6.9)	92.6 (4.6)	92.0 (5.7)
Different	Easy	93.4 (2.6)	91.3 (2.9)	91.8 (2.7)	91.6(1.8)	92.4(2.0)	91.7 (2.5)
	Hard	83.2 (2.6)	92.0 (2.9)	78.1 (2.7)	76.2 (1.8)	74.0 (2.0)	76.4 (2.5)

Table 7

Mean Task 1 Response Time (and standard error) in ms. as a Function of Task Difficulty and SOA in Experiment 2

Difficulty	*SOA*					
	100	200	300	500	700	1000
Easy	1314 (7)	1588 (11)	1417 (10)	1399 (8)	1550 (11)	1504 (9)
Hard	1390 (8)	1501 (10)	1547 (9)	1575 (13)	1711 (16)	1499 (8)

Standard errors were computed by taking the standard error of the difference scores between subjects' response times on easy and hard trials.

Table 8

Mean Task 2 Accuracy (and Standard Error) as a Function of Easy and Hard Same/Different Trials in Experiment 2

Condition	*Difficulty*	*SOA*					
		100	200	300	500	700	1000
Same	Easy	87.0 (4.9)	89.1 (1.8)	89.2 (4.7)	90.8 (3.1)	91.4 (3.4)	91.0 (3.1)
	Hard	82.8 (4.9)	89.9 (1.8)	89.6 (4.7)	85.8 (3.1)	89.3(3.4)	90.1 (3.1)
Different	Easy	81.2 (3.3)	86.9 (3.7)	87.5 (4.9)	92.1 (2.0)	91.9 (2.6)	89.5 (4.5)
	Hard	83.5 (3.3)	84.1 (3.7)	88.2 (4.9)	86.1 (2.0)	84.5 (2.6)	85.1 (4.5)

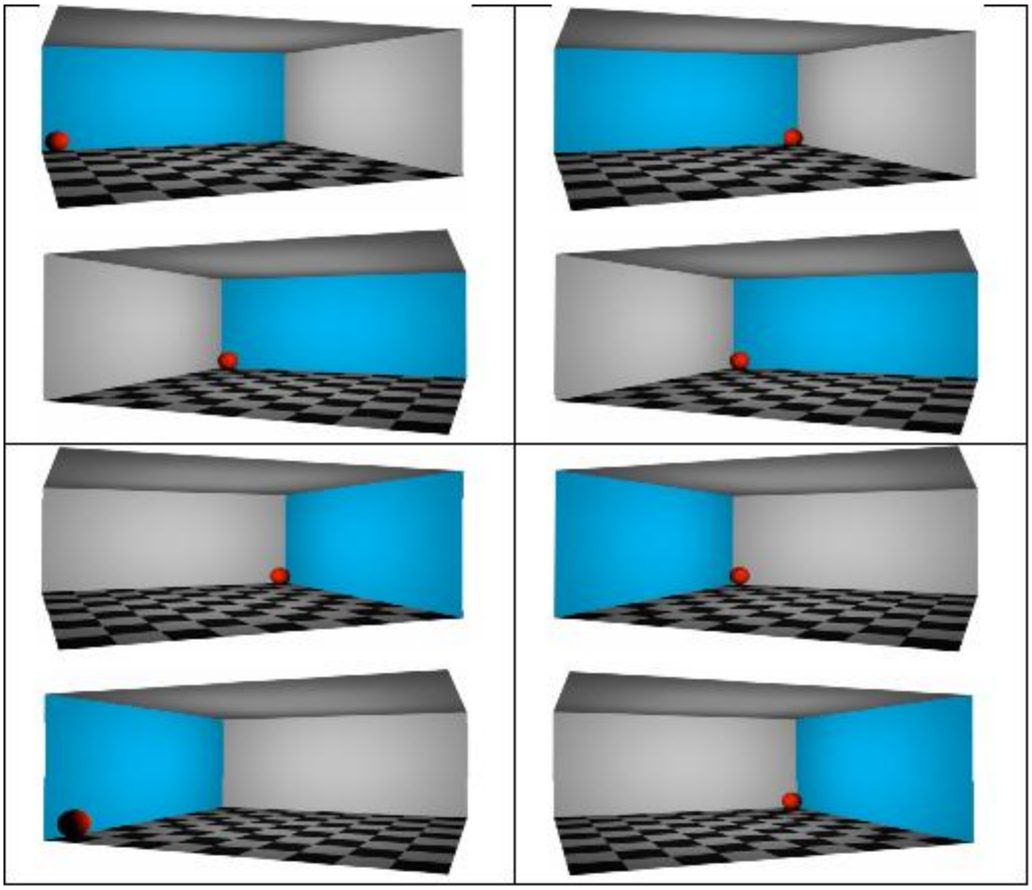

Figure 1. Sample stimuli in Experiment 1. Top left: An easy/same trial. Top Right: An easy/different trial. Bottom Left: A hard/same trial. Bottom Right: a hard/different trial.

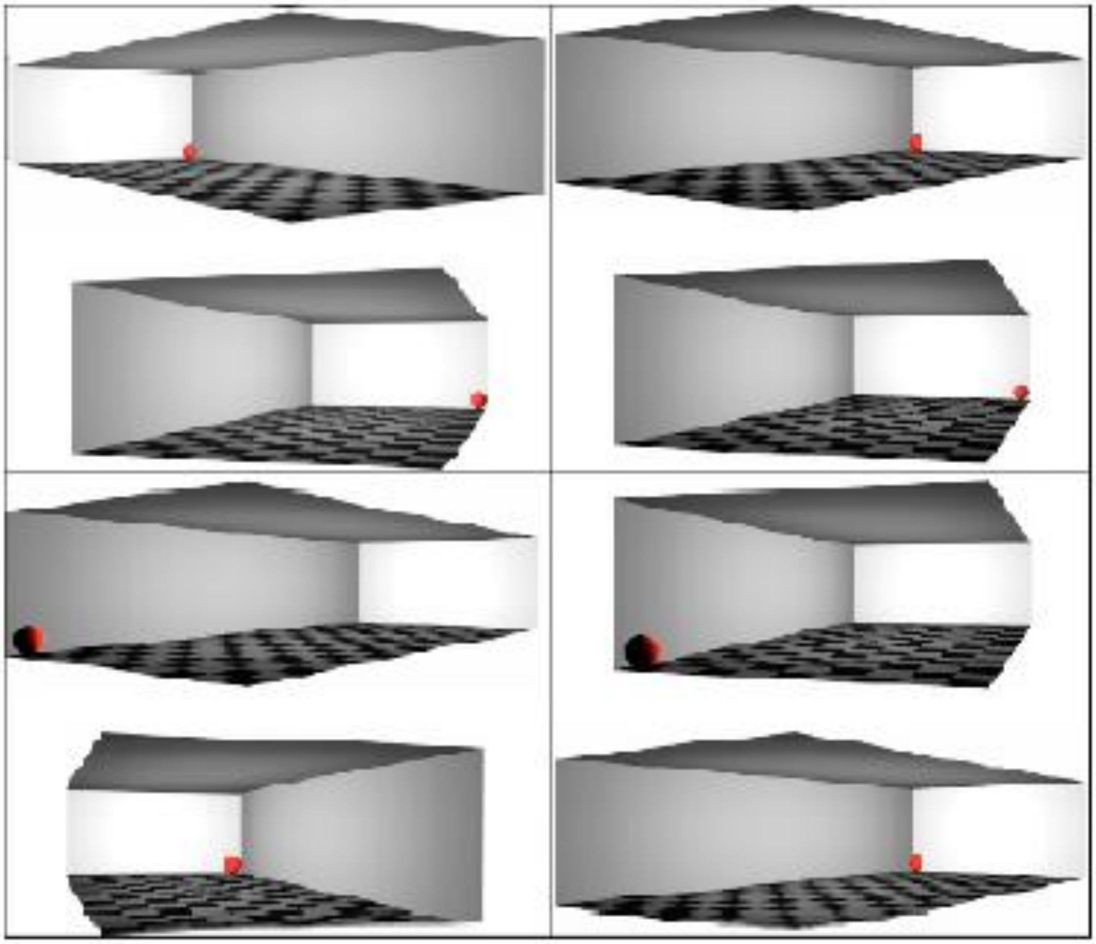

Figure 2. Sample stimulus in Experiment 2. Top left: An easy/same trial. Top Right: An easy/different trial. Bottom Left: A hard/same trial. Bottom Right: a hard/different trial.

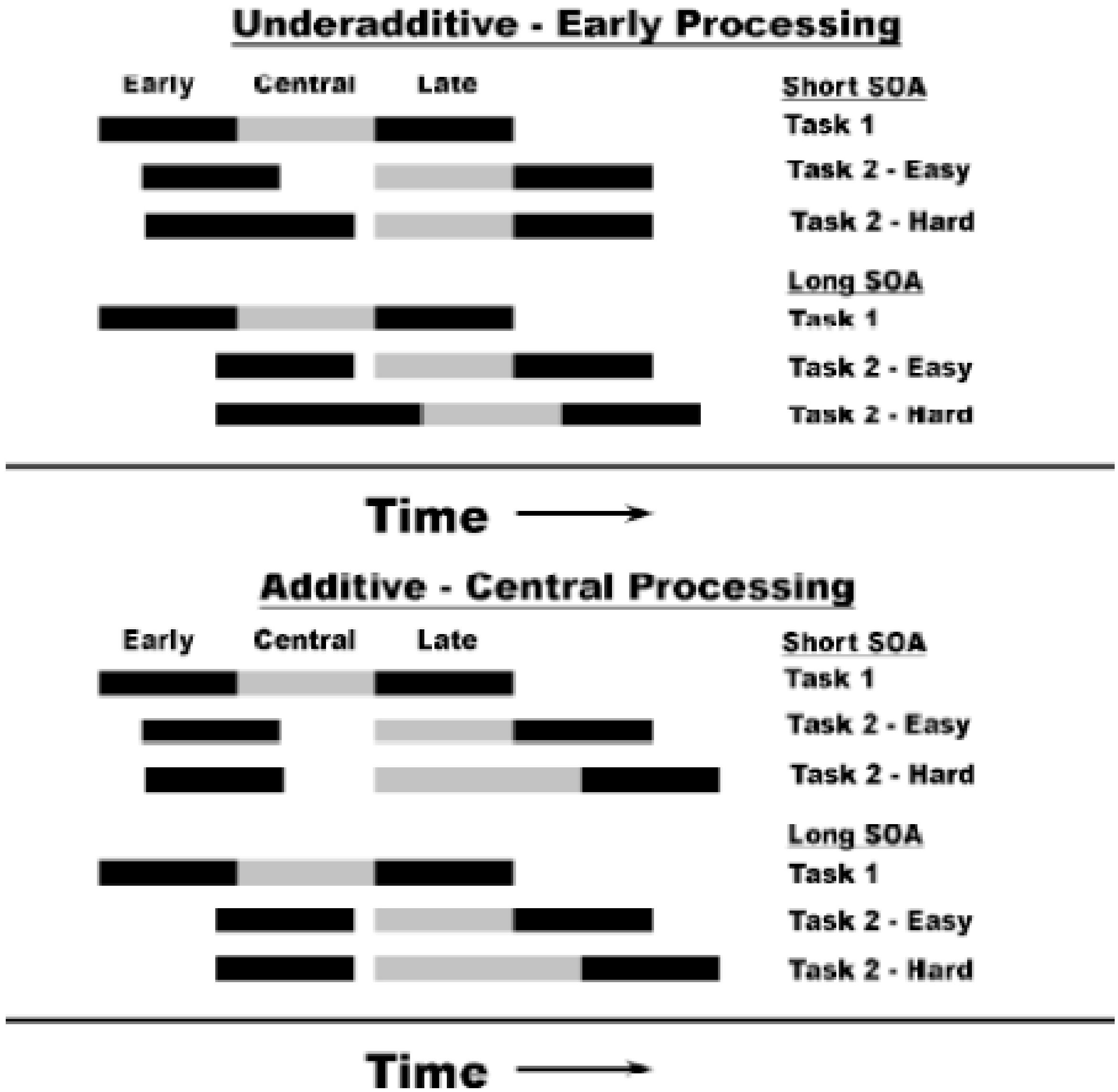

Figure 3. Graphic representation of how underadditive and additive effects are produced in the PRP paradigm from the bottleneck theory of processing. The underadditive effect is characterized by no response time difference between easy and hard trials at short SOA, while additive effects are characterized by response time differences across all SOAs.

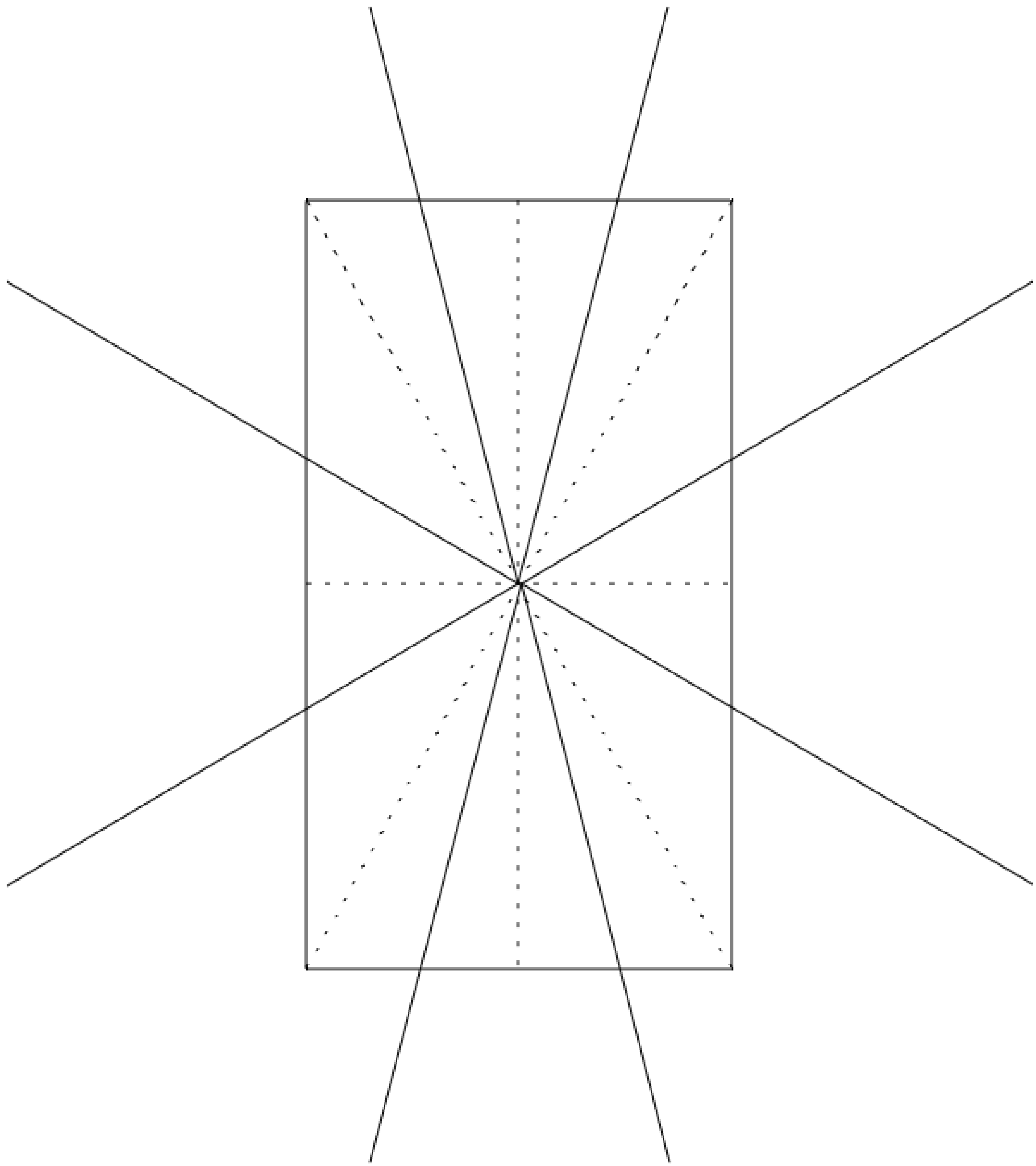

Figure 4. Graphic approximation of camera angles. The dashed lines show the initial bisections. The solid lines shows how the eight segments were then bisected to determine the camera angles. Starting with the bottom left location, and moving around the rectangle counter-clockwise, the camera angles are 13º, 43º, 133º, 167º, 193º, 223º, 317º, and 347º.

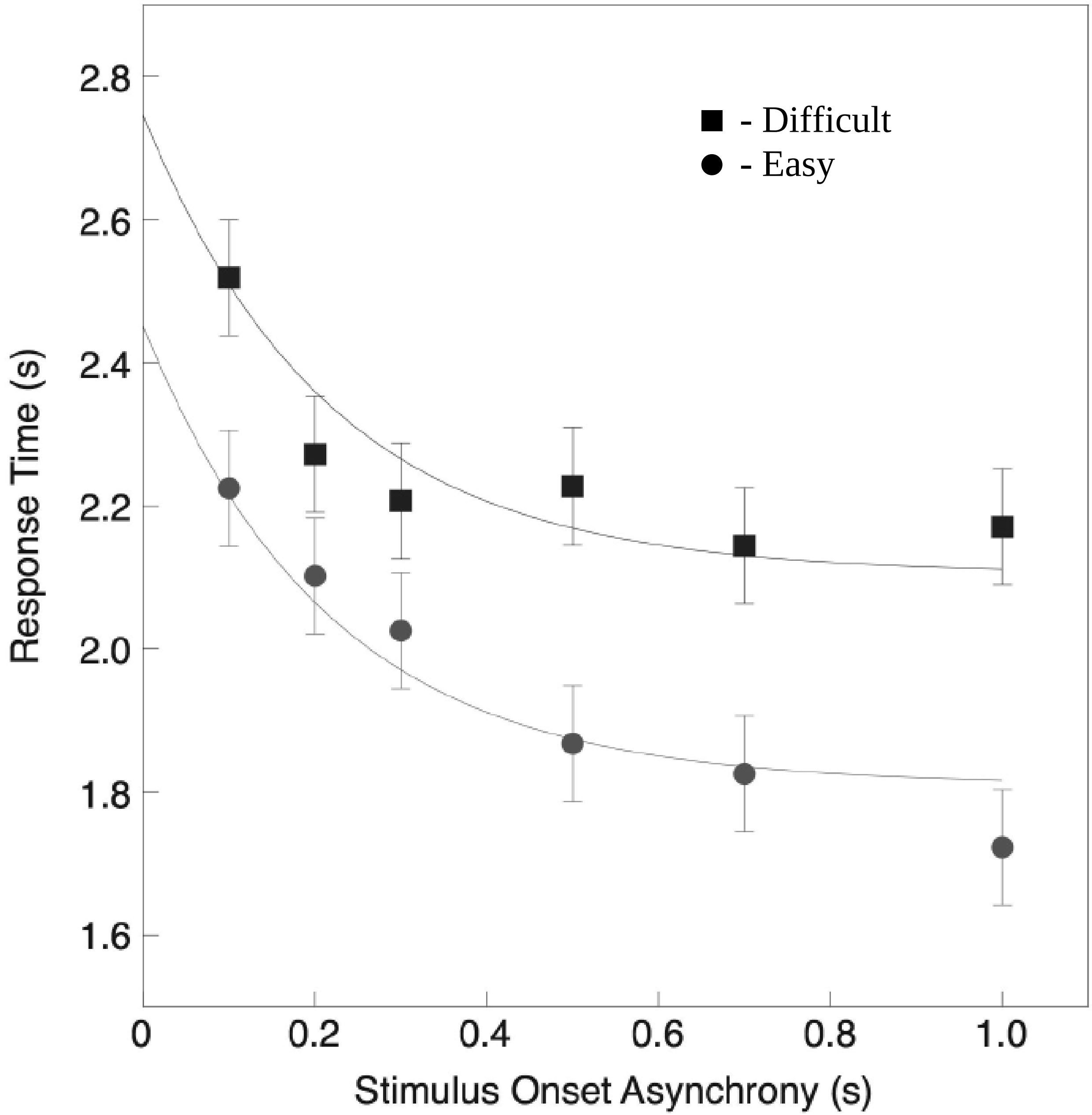

Figure 5. Mean response times for easy and difficult trials, by SOA for Task 2 in Experiment 1. Trend lines were fit with common exponential declines towards an asymptote.

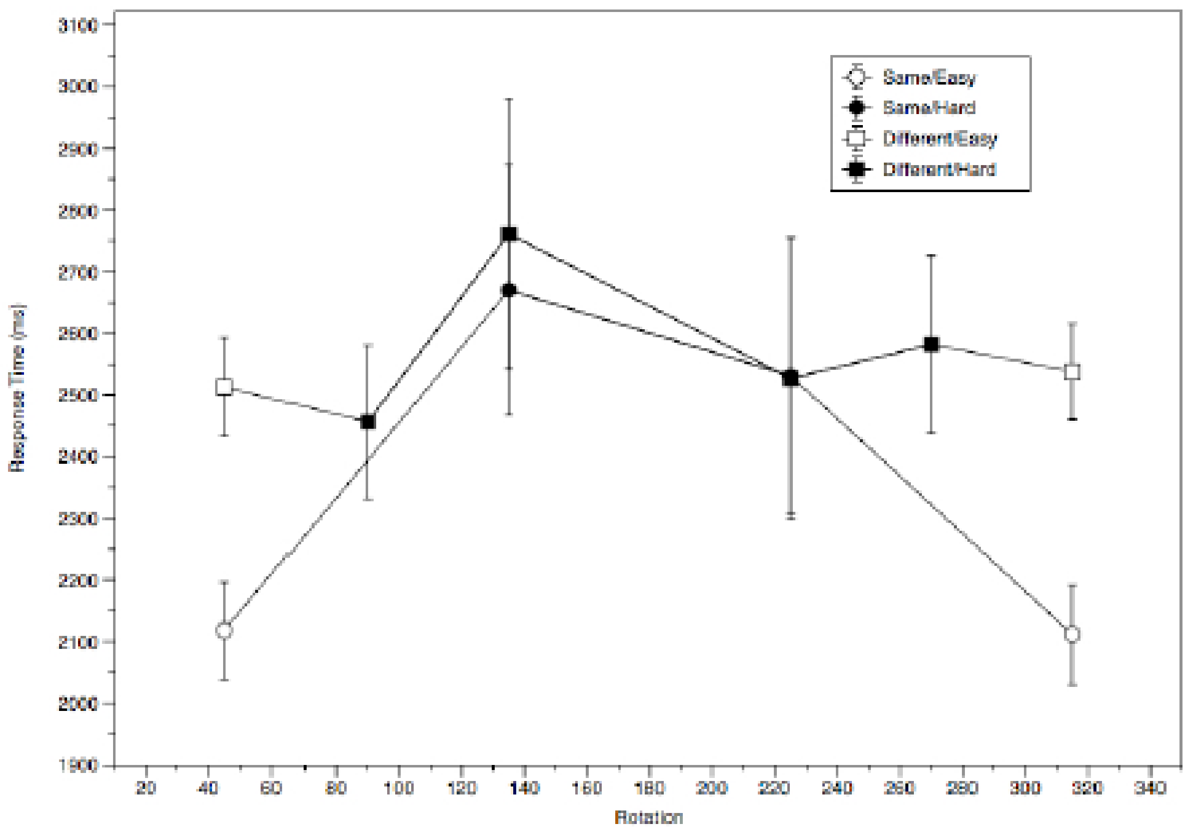

Figure 6. Mean response times for same and different trials in Experiment 1 as a function of task difficulty and rotational disparity between the two images in Task 2.

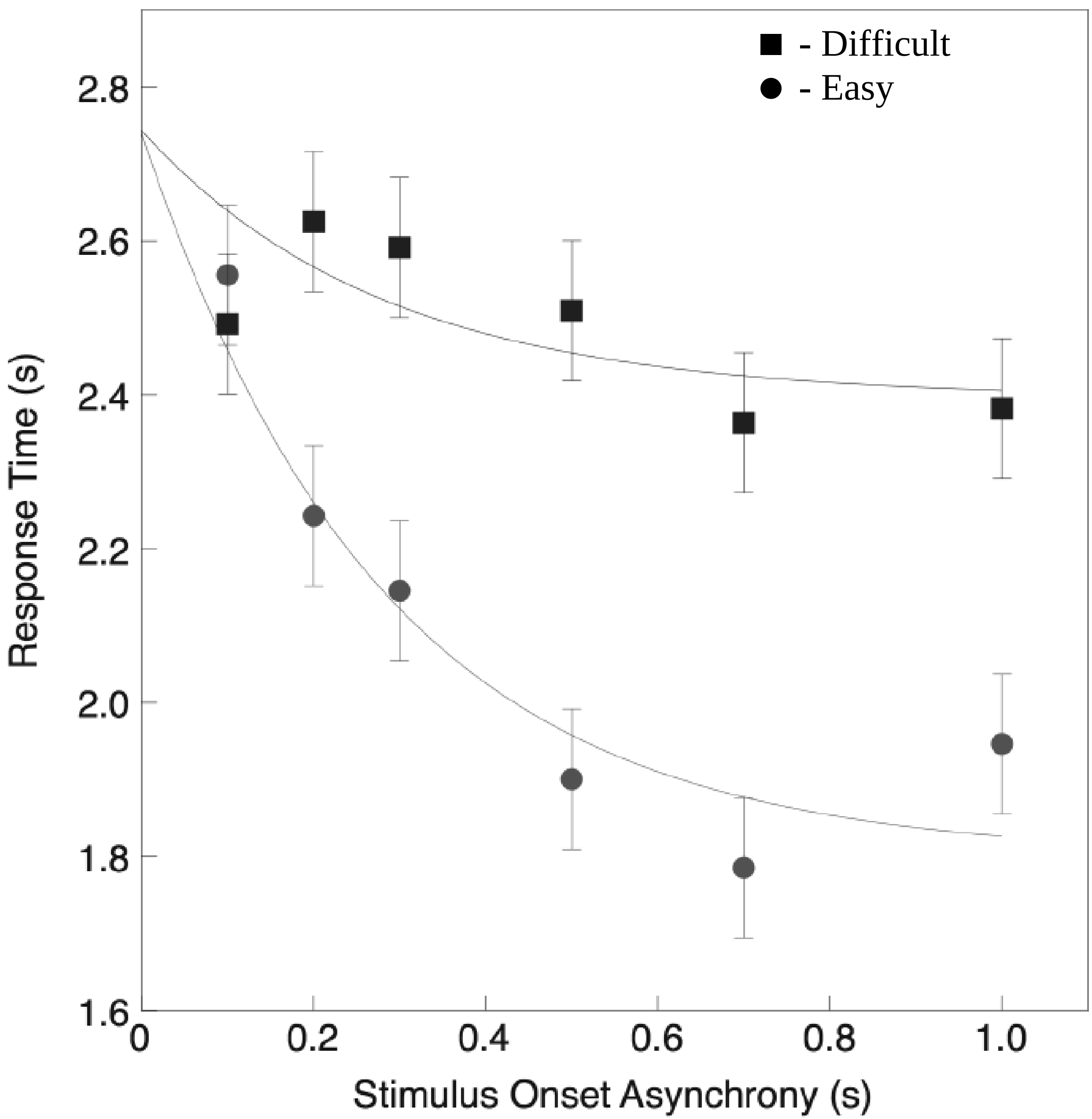

Figure 7. Mean response times for easy and difficult trials, by SOA for Task 2 in Experiment 2. Trend lines were fit with exponential declines towards an asymptote.

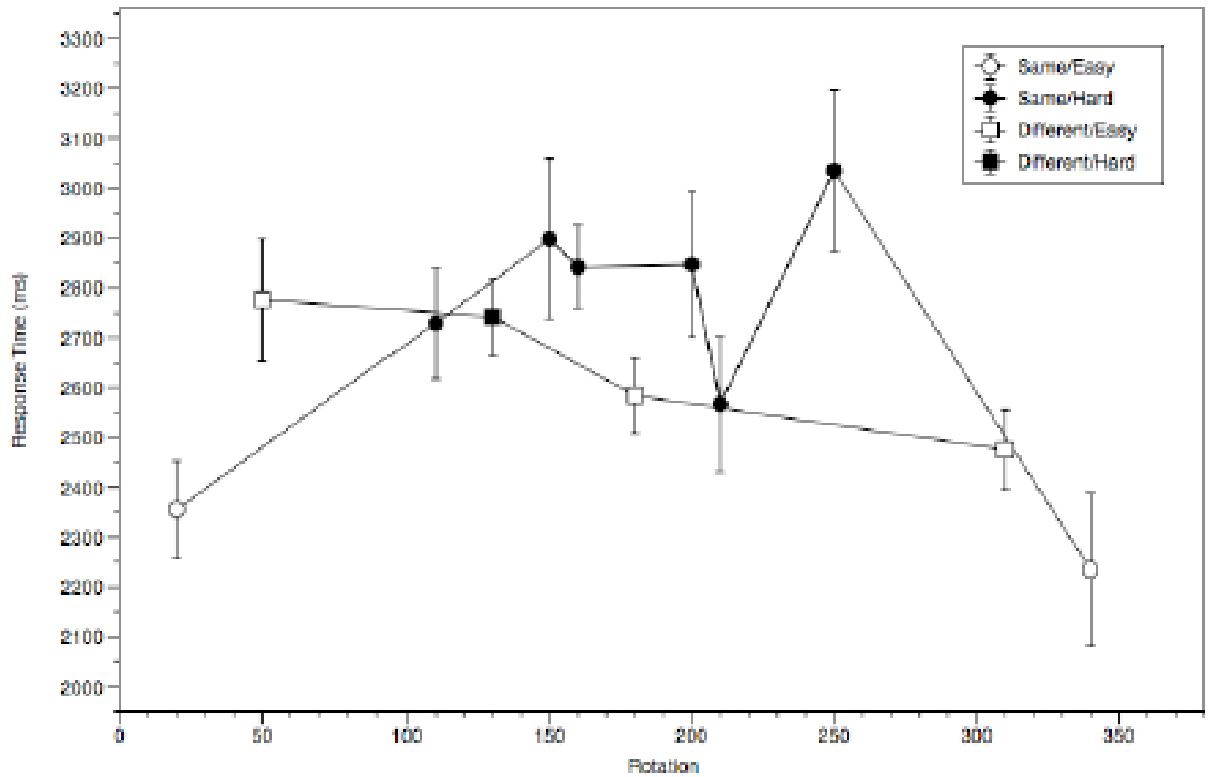

Figure 8. Mean response times for same and different trials in Experiment 2 as a function of task difficulty and rotational disparity between the two images in Task 2.