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Intra and inter hemispheric dynamics revealed by reaction time in the Dimond paradigm: A quantitative review of the literature

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ABSTRACT

In stimulus matching tasks requiring discrimination of two unilaterally or bilaterally presented stimuli (Dimond paradigm), a well established *intrahemispheric processing bottleneck* model predicts that an increase in task difficulty as measured by reaction time should provide an advantage to bilateral stimulations. The purpose of the current investigation was to review the entire relevant literature on the Dimond paradigm and identify the experimental variables which reliably yield such effects. Forty nine experimental effects compatible with the "intrahemispheric processing bottleneck" model and 26 contrary effects were found. Manipulation of the complexity of the stimulus matching criterion significantly produced *intrahemispheric bottleneck effects*. This effect was also significantly greater when non-target stimuli required heavier processing. These two findings support the intrahemispheric bottleneck model: computationally complex tasks seem to overload a hemisphere's processing capacity, an effect seen in the unilateral presentation conditions. However, manipulating the similarity of target stimuli produced contrary effects. Contrary effects were also obtained more readily when two physical matching tasks were compared. These two latter effects may best be explained as low level visual-perceptual limitations of interhemispheric transfer or integration.

1. Introduction

Experimental research using the visual half fields as the independent variable and reaction time (RT) as the dependent variable has been repeatedly exploited to study brain function. Hemispheric lateralization of cognitive functions has been extensively studied with the divided visual fields paradigm, separating the left visual field from the right visual field. Recognition tasks are most common in this paradigm. These tasks typically present one stimulus at a time in either visual field. Speed and accuracy of responses to stimuli presented in the left visual field are then compared to those obtained when stimuli are presented in the right visual field. The early processing of stimuli presented to one visual field occurs in the contralateral hemisphere (Bourne, 2006). Accordingly, left field advantages were thought to reveal right hemisphere specialization, and right field advantages were linked to left hemisphere specialization. With this approach, verbal stimuli were found to be processed faster or more accurately when presented to the right of a fixation cross while visuospatial material was processed faster or more accurately when presented to the left visual field (Durnford & Kimura, 1971; Laeng, Øvervoll, & Ole Steinsvik, 2007; Chiarello et al., 2009). This result is consistent with left hemisphere specialization for language and right hemisphere specialization for visuospatial skills observed with the anatomoclinical method and functional brain imaging (Smith, Jonides, & Koeppe, 1996).

However, the reliability of this experimental scheme has been questioned. For instance, RT and accuracy in a verbal recognition task are far from being able to replace the Wada procedure to determine whether language is lateralized in the left or right hemisphere of epileptic patients in pre-surgical tests (Channon, Schugens, Daim, & Polkey, 1990). The major problem with this approach is that in neurotypical participants, the cerebral commissures are extremely efficient in rapidly relaying information, so that hemispheric specialization cannot be reliably identified (Ivry & Robertson, 1998). Research on lateralization of brain function using RT in recognition tasks as the dependent variable has instead begun to rely on facilitation or inhibition of the brain activity of one hemisphere at a time through non-invasive cortical stimulation procedures such as TMS (Andres, Seron, & Olivier, 2005) and tDCS (Sparing, Dafotakis, Meister, Thirugnanasambandam, & Fink, 2008).

The divided visual fields paradigm studies lateralization of brain function, but does not reveal characteristics of mechanisms

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supporting interhemispheric cooperation. The primary such mechanism, interhemispheric transfer of information through the interhemispheric commissures (in particular the corpus callosum), can also be studied with tachistoscopic methods. The earliest tachistoscopic experimental design specifically used for this purpose was the Poffenberger paradigm (Poffenberger, 1912). In Poffenberger tasks, one stimulus is briefly presented to the left or to the right visual field. The participant must simply detect the stimulus and press a key with the left hand in half the trials, and with the right hand in the other half. There is no required recognition of the stimulus in the classical Poffenberger task, unlike in divided visual field tasks. If the same hemisphere processes the visual stimulus and the motor command for the response, interhemispheric transmission is not necessary. If one hemisphere receives the visual information and the contralateral hemisphere must execute the motor command, interhemispheric transmission is necessary. The difference between these two conditions, known as the crossed-uncrossed difference, is a measure of interhemispheric transfer time (IHTT). This experimental paradigm has yielded over a hundred research reports estimating IHTT in various contexts. The involvement of interhemispheric transfer generally adds about three milliseconds to RT (Braun, 1992) as measured by the crossed-uncrossed difference. IHTT can also be measured with evoked potentials, by presenting stimuli to one hemifield and observing the latency required for the spread of event-related activity from one hemisphere to the other. In Poffenberger detection tasks, the crucial evoked potential IHTT measure is obtained at frontal sites (Thut et al., 1999). Longer evoked potential IHTT can also be observed with occipital (Saron & Davidson, 1989) and parietal (Moes, Brown, & Minnema, 2007) electrodes, hinting that interhemispheric transmission of perceptual information also occurs on these tasks, but is not related to the crossed-uncrossed difference. It has become clear that in Poffenberger detection tasks, what is detected with the crossed-uncrossed difference is the interhemispheric transfer of a motor intention (Iacoboni & Zaidel, 2004). This result leaves few possibilities for novel experimental exploration taking into account more complex brain activity, such as the underlying hemispheric specialization or particularities of the interhemispheric commissures.

The study of interhemispheric dynamics with brain-inspired tachistoscopy remains a promising field of research due to the Dimond paradigm. Dimond (1969) introduced a tachistoscopy paradigm that in principle allows for simultaneous inference testing of intra and interhemispheric dynamics underlying simple neural relay, but also attention and cognition. The Dimond paradigm continues to generate interest as indicated by continuing and numerous publications. Unlike divided visual field recognition tasks, Dimond tasks require comparison of two stimuli which are simultaneously presented unilaterally in one condition, and bilaterally in another. Pairs of stimuli presented in one visual field are initially processed only by the receiving hemisphere whereas pairs presented bilaterally initially impose processing of one target stimulus in each hemisphere. In unilateral presentations there is no requirement for interhemispheric communication of visual or cognitive information, but the burden of early stimulus processing falls entirely on one hemisphere. In contrast, bilateral presentation requires interhemispheric transfer of visual or cognitive information so that the target stimuli may be compared, but the burden of early stimulus processing is spread between the two hemispheres. Matching tasks are most often employed because they are an easy way to impose interhemispheric transfer of information from one hemisphere to another. A comparison of the reaction time (RT) or error rate of the unilateral and bilateral conditions can reveal characteristics of the relations between the two hemispheres of the brain. Two classes of mechanisms potentially able to explain unilateral field advantages (UFA) and bilateral field advantages (BFA) in RT data come to mind. Limits of early processing of the single hemisphere may provide advantages to bilateral presentations, but limits of interhemispheric communication may provide advantages to unilateral presentations. Such brain dynamics need not be mutually incompatible.

Though manipulation of the size of the BFA through changes in experimental conditions had previously been reported, Banich & Belger (1990) were the first to obtain a significant UFA and a significant BFA in the same experiment, thereby popularizing a new research field centered on experimental manipulation not only of the size, but also of the direction of the effect. They obtained this first result by manipulating "computational complexity", defined as the number of processing steps required for a decision. This factor is a measure of task complexity. An easy version of their task required a response when two letter-shaped stimuli were physically exactly identical, while a more difficult version required a response when two stimuli represented the same letter, irrespective of capitalization. Visual identification and comparison was sufficient for the first task but at least one further step, the decoding of the visual stimulus as a linguistic symbol, was necessary for the second task. It is the complexity of the matching criterion which they manipulated. The easier physical matching task yielded a UFA while the more difficult letter-name matching task required more processing steps and accordingly yielded longer RT as well as a BFA. It is not the addition of a verbal component that was emphasized in the interpretation of this experiment. Rather, the modification of the match criterion was designed specifically so that a physical matching strategy would not be sufficient to accomplish the task.

The explanation of this effect given by Banich (1998) was that the necessary processing steps in computationally simple tasks are more efficiently accomplished by one hemisphere alone in order to avoid the cost of interhemispheric transfer. However, in more complex tasks one hemisphere cannot do the task efficiently by itself. The processing demands of the task overwhelm its processing capacity, creating an "intrahemispheric bottleneck". Anything that the hemisphere cannot process now, because it is too busy, must be delayed. It then becomes advantageous to split the early processing steps between the two hemispheres and to take advantage of their parallel processing capabilities. In these more complex tasks, the cost of interhemispheric cooperation becomes minimal compared to the cost of the intrahemispheric processing bottleneck. Experimental effects supporting this model have frequently been reported in the literature (see our review below). However, effects contradicting this model have also been reported, albeit less frequently (see our review below). Theoretical explanations for the second category of findings have barely been considered.

While the effect of the complexity of the matching criterion on interhemispheric comparison is usually the effect of main interest in these studies, we note that it is not always the largest effect in terms of RT. Manipulations of the level of similarity between target stimuli, of the number of additional non-target stimuli, of the position of target stimuli and of the type of stimuli used are sometimes not statistically analyzed or otherwise overlooked even when they appear to have more important effects on RT, at first glance, than the experimental variable of traditional interest.

A generalization of the model proposed by Banich to all studies within the Dimond paradigm might be possible. Mean RT of the experimental condition can be used to define, *a posteriori,* which of two conditions is easy and which is difficult. The rationale for the use of RT as a measure of task difficulty is that an individual whose performance on a task is faster than the others' would certainly be said to be more capable. Therefore RT seems to measure capacity, so long as accuracy rates are also maintained. If one change is introduced to a task and the average RT of a group of individuals rises, the explanation that the capacities of the