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A generalized role of interhemispheric interaction under attentionally demanding conditions: evidence from the auditory and tactile modality

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Abstract

The present study investigated whether dividing critical information across the hemispheres in the auditory and tactile modalities aids performance more for computationally complex rather than computationally simpler task—a pattern previously observed in the visual modality [Cortex 26 (1990) 77; Neuropsychology 12 (1998) 380; Neuropsychologia 30 (1992) 923]. We conducted two experiments, one in the auditory and one in the tactile modality, that were analogous to those previously performed in the visual modality. In agreement with previous findings, for both modalities we observed that the performance advantage exhibited for within-hemisphere processing in the computationally simpler condition (that required fewer steps to reach a decision) was diminished in the computationally more complex condition. In the auditory experiment we also manipulated computational complexity by varying the amount of time available for processing information. The within-hemisphere advantage in performance was also significantly reduced when complexity was increased through temporal manipulations. These findings suggest that the brain may use interhemispheric interaction as a general strategy to increase computational resources, independent of sensory modality and the manner in which computational demands are increased.

Keywords: Interhemispheric interaction; Corpus callosum; Attention; Auditory processing; Dichotic listening; Tactile processing

1. Introduction

A robust body of experimental evidence in the visual modality indicates that as computational complexity in a task increases, within-hemisphere processing (in which all information critical for a task is directed to one hemisphere) becomes less efficient than across-hemisphere processing (in which the critical information is divided across the hemispheres). In these studies task complexity has been increased either by increasing the number of steps necessary to reach a decision [6–8,12,42] or by increasing the demands placed on selective attention [8,41]. Regardless of its source, added computationally complexity will tax our attentional resources. Hence these findings suggest that, at least in the visual modality, interhemispheric interaction (IHI) becomes relatively more advantageous, as compared to within-hemisphere processing, under attentionally demanding conditions. Nonetheless, these studies raise the question of whether these effects of IHI generalize to other sensory modalities, such as the auditory and tactile ones. In this paper we address the issue of whether IHI is a *general strategy* that the brain may use to increase the attentional resources available when task demands are high, regardless of the sensory modality involved.

In our prior studies we have repeatedly found that within-hemisphere processing is less efficient than across-hemisphere processing for a name-identity task, in which an individual must decide if two letters share the same name (e.g. “A” and “a”), but not for a physical-identity task, in which an individual must decide if two letters are identical (e.g. “A” and “A”) [7,11,12]. From a theoretical perspective, we posit that within-hemisphere processing becomes less advantageous than across-hemisphere processing because of an interaction between two opposing forces [2,3,5,7,8], each of which aims at reaching the most efficient performance (i.e. the fastest and most accurate response with the

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least amount of brain resources). Our theoretical account is based on three main assumptions. First, we assume that the processing capacity of the brain is limited [25], and therefore there are limitations to the amount of processing that can be done within a given time. Second, we consider the two hemispheres as two separate processors, with their own pool of resources (see [18] for a review) which can couple [7,8,11,12]) or decouple [35,42] their processes to increase the brain's computational power. As long as each hemisphere can perform at least some significant portion of the task in question, the processing can be divided between them. There are only a few instances in which this division is not possible (e.g. only the left hemisphere can perform the phonetic processing necessary to make a decision about rhyme) [11], and in these instances the IHI advantage disappears. Third, there is an inverse relationship between "efficiency" of processing and "amount" of processing that needs to be done per time unit. It is this inverse relationship that allows us to define complexity (e.g. the more computations are necessary, the more resources are needed to give an efficient performance). On the one hand, interhemispheric processing is likely to increase the processing resources that can be brought to bear upon task performance, because each hemisphere is a somewhat independent information processor [17]. However, interhemispheric processing incurs additional costs not associated with intrahemispheric processing, because it requires integration of information between the hemispheres via the corpus callosum, the major cortical commissure relaying information between the hemispheres. This integration takes time and is also likely to require additional processing steps. When computational complexity is relatively low, the benefits associated with greater computational power afforded by dividing processing between the hemispheres are not large enough to outweigh the costs associated with integrating information across the hemispheres. As a result, processing is more efficient when all information is directed to a single hemisphere (i.e. a within-hemisphere advantage). In contrast, when computational complexity is relatively higher, the benefits associated with greater computational power begin to outweigh the costs of integrating processing between the hemispheres. As task demands increase, there is a shift in efficiency from within- to across-hemisphere processing, the size of which depends on the relative difference in complexity between the two tasks. If the difference in processing demands across the two tasks is dramatic, a switch from a significant within- to a significant across-hemisphere advantage is observed. If the difference in complexity between the two tasks is less dramatic, either no difference is observed between within- and across-hemisphere processing, or across-hemisphere processing is slightly more advantageous than within-hemisphere processing. Results across a large number of studies in young adults [2,3,6–8,11,12] as well as recent developmental studies with normal children and children with phenylketonuria [3,4] and those with elderly adults [38] confirm that a division of processes becomes more efficient than within-hemisphere processing as the relative task complexity increases.

If our theoretical account of these effects is correct, then we predict that this pattern of results should be observed regardless of sensory modality. Until recently, though, all the evidence that IHI is beneficial to performance as task demands increase has come from studies in the visual modality (see [1] for a review). This fact raises the question of whether previous findings in the visual modality reflect a modality-specific phenomenon or not. This is an important question because as Banich [2] pointed out, IHI is not a unitary phenomenon. Rather, IHI for different sensory modalities occurs through functionally [15,16,20,37,39] and anatomically [34,39] distinct channels of the corpus callosum. Because the primary sensory regions of the brain are connected by distinct regions of the callosum ([15,27], see also [23] for a comprehensive review) it is possible that the findings we have attributed so far to an attentional involvement of IHI may instead reflect a specific attribute of IHI for visual information or visual attention, and have little to do with the modulation of attentional capacity in general. Therefore, if we want to claim that IHI is a general strategy that the brain uses to increase processing capacity, it becomes crucial to provide evidence that IHI becomes relatively more efficient than within-hemisphere processing as attentional demands increase, not only in the visual modality but also in other modalities as well.

Our motivation to determine whether the IHI effects observed previously generalize to other modalities is also driven by a wish to determine the possible mechanisms of IHI and the nature of information that is being transferred. One possible way to examine the nature of the information being relayed across the hemispheres is to test whether the source of the across-hemisphere advantage usually observed in the visual modality for the computationally more complex task is really a division of processes, as we argue [5,7–12] or whether it rests on differential transfer of information depending on how it is represented [30,31]. Marsolek and colleagues suggest that our results can be best understood by the type of visual representations that are optimal for performing the physical- and name-identity tasks, respectively. They have suggested that there are two main types of visual representations, each of which relies on a different neural subsystem [30]. One subsystem, the "specific-visual form" subsystem, recognizes specific instances of forms (e.g. "A" and "A" are physically identical; "A" and "B" are not) and maps them onto a form-specific representation. The other one, an "abstract-visual form" subsystem, recognizes abstract categories of visual forms (e.g. both "A" and "a" belong to the category: letter "A") and maps them onto abstract representations. Marsolek and colleagues propose that whereas callosal transfer is fairly efficient for abstract-visual form information, it is inferior for specific-visual form information. According to their view, the across-hemisphere processing advantage for a name-identity task that we have repeatedly found in previous visual studies [7,11,12] is mainly due to the fact that the type of representation involved (i.e. abstract-visual form) is better transferred across the hemispheres than the type of representation involved in the physical identity-task (i.e. specific-visual form).

Although we disagree with this interpretation for a number of reasons that are not the main point of this paper and hence will not be discussed here, we agree with them that it is theoretically very important to try to understand the source of the relative IHI advantage as task complexity increases (i.e. either because of a division of processes, or the efficiency of transfer of different representations). Because Marsolek's theoretical approach examines IHI effects based on a theory on different types of visual representations it cannot be applied to other modalities "as is". But examination of the effects of IHI in other modalities provides another means to examine the degree to which our theoretical model, rather than one based on the nature of the representation of information transferred, is parsimonious with empirical data. If it is mainly a division of processes that makes IHI more efficient than within-hemisphere processing when complexity increases, as we suggest [7,12], then we would predict a reduction in within-hemisphere processing advantage as task demands increase, no matter what modality (and hence type of representation) is involved. On the contrary, if the across-hemisphere advantage is due to differences in the representations used on within- and across-hemisphere processing, then we would predict a different pattern of IHI effects depending on the modality, as the representation of stimuli is likely to vary across modalities.

Given the goals of the present study, it becomes essential to have a good understanding of the type of processes and representations that are involved in each of our auditory and tactile tasks, so that we can reasonably apply our existing theory of complexity to non-visual modalities. In the relative introduction for each of the auditory and tactile experiments we will therefore elucidate: (a) the task components and possible representations involved in the tasks for that specific modality; (b) how they differ from other modalities; (c) how those differences affect the level of task complexity; (d) how these factors influence our predictions on the relation between task complexity and IHI. Finally, for each experiment, we will discuss and address more specific theoretical questions about the relationship between IHI and computational complexity. In our auditory paradigm (Section 2) we not only examined whether the relationship between IHI and computational complexity generalizes across modalities, but we also examined whether IHI effects generalize across different manners of manipulating computational complexity. In our tactile paradigm (Section 3) we took yet another opportunity to test whether IHI effects are independent of modality, as the nature of complexity of the two tasks previously used in the visual modality (i.e. physical identity versus name/category identity) is quite different in the tactile modality. As such, our tactile experiment gave us a unique opportunity to examine the robustness of the relationship between IHI and task complexity.

2. Experiment 1: effects of interhemispheric interaction on performance in the auditory modality

This experiment was designed to investigate whether IHI aids task performance under computationally complex conditions in the auditory modality, as previously found in the visual modality [7,11,12]. To examine the issue of computational complexity and IHI in the auditory modality, we created a dichotic listening task that was as equivalent to the original Banich and Belger study (experiment 2 in [7]) as a transformation across modalities would allow. In that study, the less complex task was a physical-identity task in which participants decided if a target number (e.g. 1) was physically identical to one of two probes numbers (e.g. 1 and 4). The computationally more complex task was an ordinal-decision task in which participants decided if a target number (e.g. 6) was smaller in value than either of two probe numbers (e.g. 4 and 8). Like the Banich and Belger study in the visual modality [7], in the present study the stimulus consisted of a lateralized target along with two probes, each of which was presented to a different hemisphere. Since the lateralization of perceptual processing varies across modalities, we needed to consider the particulars of auditory processing in designing our task. To transport a visual paradigm into the auditory modality requires ensuring that the stimuli are lateralized so that within- and across-hemisphere trials could be compared. To do so, we adopted the dichotic listening technique, in which participants listen to two competing messages presented simultaneously, one to each ear ([13], see also [14,21,24] for a review). The dichotic listening technique lends itself nicely to laterality studies, in that when two different auditory stimuli are presented simultaneously to both ears there is relative suppression of the ipsilateral auditory pathway as compared to the contralateral one. Hence, information presented to one ear is mainly processed by the opposite hemisphere [26,32]. Because it would be difficult to present three items simultaneously in the auditory modality, we chose to modify the Banich and Belger task [7], so that the target number was presented first, followed by the two probes. To ensure that the target number was lateralized to one hemisphere, we presented it dichotically along with a foil, which in this case was always a one syllable animal name (e.g. "fox"). Following an inter-stimulus interval (ISI), the two probes were presented dichotically, one in each ear. In the within-hemisphere condition, we presented the target and matching probe to the same ear. In this manner, the critical information was received by one hemisphere, and IHI was not required to perform the task. In the across-hemisphere condition, we presented the target and matching probe to opposite ears. In this condition, the critical information was divided between the hemispheres and IHI was required to perform the task.

In this experiment we also wished to examine another important issue regarding the relationship between task complexity and IHI. In our prior studies we manipulated computational complexity through a variety of means, including the number of steps required to reach a decision [7], the number of items to be encoded and compared to a target [11], and the number of ways in which selection was required in attentional paradigms [8,40,41]. Notice that the logic behind all these manipulations is that the relatively more complex task merely requires the insertion of an additional step (insertion assumption). It is possible that such an assumption of pure insertion is not valid, and that individuals adopt qualitatively different approaches to each task (e.g. the nature of perceptual analysis varies depending on whether we make a match based on physical features as compared to the name of the item). To address this issue, we decided to also examine the effects of IHI on attentional performance by manipulating computational complexity in terms of temporal constraints, while keeping constant the number of steps required to reach a decision. Specifically, we varied processing demands in terms of the time available for stimulus processing. We chose such an approach, because Banich [10] found evidence in a pilot study that IHI aided performance more when all the task-relevant information was presented simultaneously rather than sequentially. She interpreted these data to suggest that when items are presented sequentially the number of computations that need to be performed per unit time is lessened, therefore reducing computational complexity and the IHI advantage. Such an idea is also supported by recent data from our laboratory (experiment 3 in [42]), in which we found that across-hemisphere processing appears to be invoked more when all items in a stimulus display are presented simultaneously, as compared to sequentially. If such an interpretation were correct, we would expect to find a similar effect in the auditory modality.

To change task complexity using temporal manipulations, we varied the ISI between the offset of target article and the onset of the two probes for both the physical-identity and the ordinal-decision tasks (100 versus 250 ms). Shortening the ISI decreases the time available to complete target processing before the probes are presented. Therefore, it increases the processing load per unit time and the complexity level. To make clear predictions about how task complexity should be influenced by IHI in the auditory modality, we need to carefully analyze the component processes involved in our tasks as performed in the auditory modality. In the physical-identity task, the basic steps involved are as follows: (1) stimulus detection; (2) perceptual processing of physical features; (3) a comparison of items; and (4) motor response programming and execution. With regard to the ordinal-decision task, we predicted that IHI would be advantageous because in this task computational complexity is increased. In fact, in addition to the steps described above, an additional one must be performed: that of extracting information about the value of an item. Moreover, we need to consider that varying the ISI between items can affect task complexity. That is, the amount of processing that can be performed on an item before the next item is received can vary. When items are presented with a longer ISI, more processing of the target can occur before receipt of the probes, but when they are presented with a shorter ISI, less processing of the target can occur before receipt of the probes. The length of our ISIs is also critical to our predictions, as they are so short as to ensure that only echoic processing can occur on the initial target before receipt of the two probe items. Hence, the two ISIs we have selected will not vary the nature of the representation that is present when the probe items are presented. Rather, the shorter ISI adds complexity to the task because it gives participants less time to perform initial processing of the target before the probes are presented. We also predicted that the effects of these manipulations were likely to be separable. This hypothesis was based on prior work by Belger and Banich, in which computational complexity was varied both by the number of inputs and the number of steps involved in the decision process. When the number of inputs was increased from three to five in a physical-identity task [7], the within-hemisphere advantage for the three-item task switched to a 5% across-hemisphere advantage for the five-item task, indicating that the number of items to be processed has an effect on performance. Moreover, for the five-item name-identity task [7], we obtained a 10% across-hemisphere advantage, indicating that the additional complexity imposed by the name-identity task as compared to the physical-identity task also increased the across-hemisphere advantage. These findings indicate that different types of complexity manipulation are separable and have different effects on performance [12].

In summary, based on previous findings we predicted that in our experiment we would find somewhat separable effects of manipulating complexity in terms of temporal constraints and in terms of the number of steps necessary to reach a decision. With regard to our manipulation of complexity in terms of computational steps, we expected that the advantages of within-hemisphere processing would be diminished for the more complex ordinal-decision task. With regard to our temporal constraint manipulation, we expected to observe that the advantages of within-hemisphere processing would be reduced when the ISI was 100 rather than 250 ms, as the shorter ISI increases complexity.

2.1. Methods

2.1.1. Participants

Fifty right-handed students from the University of Illinois at Urbana-Champaign, with normal hearing and no neurological impairment participated in our experiment and were compensated either $6 per hour or received class credit. All participants were right-handed, as assessed by a questionnaire that evaluated hand-preference for each of eight activities (such as using a spoon, using scissors, throwing a ball, etc.). Participants were considered right-handed if they wrote with their right hand and performed seven of the eight activities with their right hand.

2.1.2. Equipment

We used a Realistic Stereo microphone to record our auditory stimuli and then used Sound Edit Pro 16 software on a Macintosh Centris 650 to digitize, edit, and create the sound samples. SuperLab 1.68 software was used to create the experimental paradigm and to present the auditory stimuli through Realistic Stereo headphones. We verified that a consistent and comparable auditory signal was provided through both the left and right headphones, so as to ensure matched auditory input to each ear. During the experimental session our auditory stimuli were presented through a Power Macintosh 7100/66 or a PowerMacintosh G3. Timed presentation of trials was controlled by Superlab 1.68, which was also used to collect participants' response choices as well as their response latencies.

2.1.3. Stimuli

Our target and probes were monosyllabic numbers from one to nine, with the exclusion of seven, because it is composed of two syllables. The foils were monosyllabic animal names: bat, dog, ant, cow, pig, lamb, moth and fox. Both for the 250 ms ISI and for the 100 ms ISI condition, the numbers and foils were recorded in a female voice while keeping intonation, basic frequency and intensity constant. We used Sound Edit Pro 16 to record, digitize (at a rate of 22,000 Hz) and store our auditory stimuli on Iomega Zip Disks. These stimuli were then edited and synchronized for onset, intensity (70 dB) and length (450 ms). The criterion for temporal alignment for the different words was the onset of articulatory release. Stimuli were made the same length by shortening the vowel part of each word. Then they were normalized and enveloped (a procedure by which sounds are ramped in intensity) to remove clicks at the beginning and end of the words due to editing.

From these stimuli, we created trials that consisted of two dichotic pairs of auditory stimuli (Fig. 1a and b). The first pair was always composed of a target number and an animal name (the foil). The second pair was always composed of two numbers (the probes). Half of the trials were match trials, in which the target and one probe would lead to a match decision. The other half were mismatch trials, in which neither of the probes led to a match decision with regards to the target. As in previous experiments in the visual modality (e.g. [7,11,12]), half of the match trials did not require IHI, because the target and matching probe were presented to the same hemisphere (within-ear trials). On half of these trials, the target and the matching probe were presented to the left

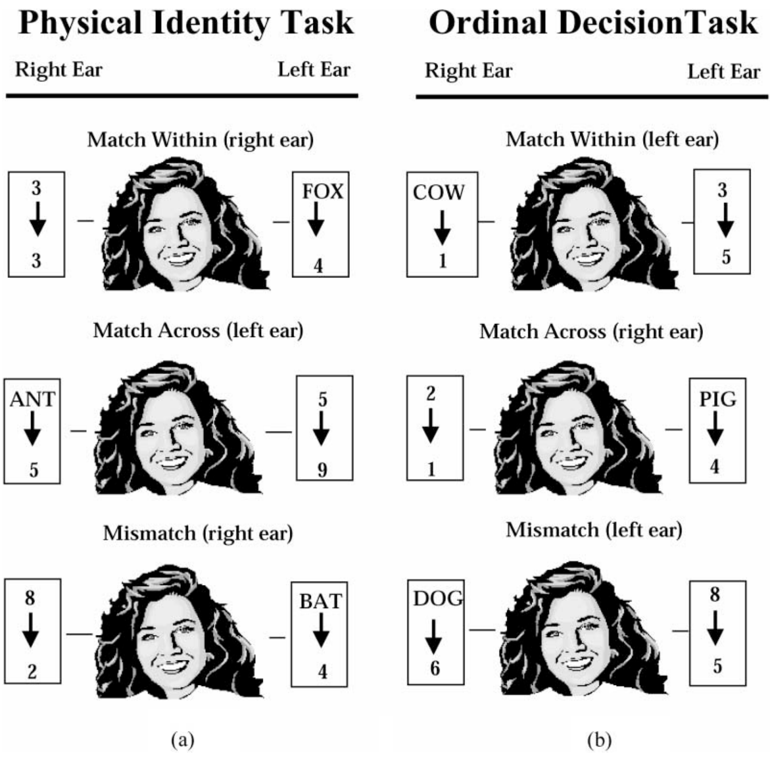

Fig. 1. Experiment 1: sample match and mismatch trials. Trials are distinguished by the ear to which the target is presented (i.e. on left ear trials, the target is presented to the left ear). The target number was presented at the beginning of each trial, together with a foil (i.e. animal name). Then, after an ISI of 100 or 250 ms (depending on the ISI condition) two probe numbers were presented: (a) trial types for the physical-identity task, in which participants decided whether the target number was identical to either of the two probes; (b) trial types for the ordinal-decision task, in which participants decided whether the target number was smaller in value than either of the two probe numbers.

ear, and on half to the right ear. The other half of our match trials required IHI, because the target and matching probe were presented to opposite hemispheres (across-ear trials). On half of the match trials and on half of the mismatch trials the target was presented to the left ear, whereas for the remaining trials the target was presented to the right ear. In our nomenclature, we designate those trials in which the target was presented to the left ear as left-ear trials, and those in which it was presented to the right ear as right-ear trials.

2.1.4. Procedures

Participants performed the physical-identity and ordinal-decision task in a 1 hour session. They were initially screened for handedness and also performed the Chimeric face test (CFT) [28] to assess individual differences in asymmetric hemispheric activation [29]. Since this data were collected for other purposes, we will not discuss them here. All of our participants were screened for normal hearing and wore headphones throughout the experiment. Then participants were introduced to the actual experimental session. At the beginning of each task, participants were given instructions and 16 practice trials with feedback, followed by two blocks of 64 experimental trials each without feedback. For both tasks, each trial began with a warning beep. After a 1 s silence the first dichotic pair, consisting of the target and foil, was presented for 450 ms. Then there was an ISI of either 250 or 100 ms (depending on the group to which a subject was assigned) between the offset of the first pair and the onset of the second pair of items, which was presented for 450 ms. Participants had 2000 ms to give a forced-choice response via key press on computer. They pressed one key for match decisions and a different key for mismatch decisions. After participants gave their response there was a 2000 ms inter-trial interval, followed by the next trial. For each task, half of the participants started the first block of 64 trials with “headphone orientation 1” (right ear/right channel, left ear/left channel), and half started with “headphone orientation 2” (right ear/left channel, left ear/right channel). After the first block of trials, the headphone orientation was switched and participants performed another block of trials for the same task. At the beginning of each block, the experimenter told participants which response key to use for match and mismatch trials, and the hand and headphone orientation they would start with. Starting hand, response key (g, h) and initial headphone orientation were counterbalanced across participants.

Participants first performed the physical-identity task and then the ordinal-decision task. We always had them perform the computationally less complex physical-identity task before the more complex ordinal-decision task to minimize the possibility that strategies from one task would influence the other. Performing the ordinal-decision task first might prime individuals to think about number values, which could carry over to the physical-identity task, and circumvent basing the decision on physical identity. In contrast, since paying attention to physical identity would not allow an individual to correctly perform the ordinal-decision task, performing the physical-identity task first would be highly unlikely to influence how the ordinal-decision task was performed. Previous studies have shown that a lack of counterbalancing in task order is not problematic, since the same pattern of results (i.e. a reduction in the within-hemisphere processing advantage for the more complex task) has been previously found both when the less complex task is performed before the more complex task [6,10], and when task order is counterbalanced [17].

Finally, we should point out that our task manipulation (i.e. physical versus ordinal task) is not likely to produce practice effects from one task to the other, since the two tasks rely on different computational steps. Therefore we used “task” as a within-subjects factor. On the contrary, if we used our ISI manipulation (i.e. 250 versus 100 ms interval between presentation of target and probes) as a within-subject factor, participants would perform our two tasks twice, once for each ISI, which may be more likely to produce practice effects. Hence, we decided to use a between-subjects design for our ISI manipulation.

2.2. Results

We excluded from our data analyses participants who did not reach a mean accuracy level of 75% in either of the two tasks. We chose this conservative criterion of exclusion because we only wanted participants who were able to perform tasks with a reasonable degree of accuracy. If accuracy for a task was very poor, we were concerned that it might limit the conclusions we could draw regarding IHI. Our final sample included 39 subjects, 21 in the 100 ms ISI condition and 18 in the 250 ms ISI condition. We excluded from the RT analysis those trials in which RT were less than 200 or more than 2000 ms (so as to avoid outlier effects), or in which participants pressed the wrong key. These excluded trials were classified as incorrect responses in the accuracy analysis.

A repeated measures ANOVA was carried out on match trials separately for RT and percent correct using the between-participants factor of ISI (250 and 100 ms) and the within-participants factors of task (physical-identity, ordinal-decision), trial type (within-hemisphere, across-hemisphere) and ear of target (left, right). For the purposes of our study we will focus our discussion on mean RT and accuracy for match trials, since only match trials have the critical comparisons (i.e. within-hemisphere and across-hemisphere) to examine whether IHI benefits performance as task complexity increases. We refer the reader to a different study [8] for an exhaustive discussion of how mismatch trials affect IHI findings. In our discussion of the results, we will emphasize how interhemispheric processing affects manipulations of computational complexity, both by (1) the number of steps needed to reach a decision; and (2) the length of the ISI.

2.3. Reaction time

2.3.1. IHI effects on steps required to reach a decision

We obtained a main effect of task ($F\,(1, 37) = 29.23$, $P < 0.0001$), in that responses to the physical-identity task were faster (739 ms) than to the ordinal-decision task (921 ms). We also obtained a main effect of trial type ($F\,(1, 37) = 40.40$, $P < 0.0001$), which indicated that that responses to within-ear trials (for which no IHI is needed) (780 ms) were faster than to across-ear trials (for which IHI is needed) (880 ms). Importantly for our investigation, both of these main effects were modified by a significant interaction of task by trial type ($F\,(1, 37) = 11.42$, $P < 0.002$). In accord with our hypothesis, tests of simple effects revealed that for the computationally less complex physical-identity task, responses were 145 ms faster to within-ear trials than to across-ear trials ($F\,(1, 37) = 60.84$, $P < 0.001$). For the computationally more complex ordinal-decision task, there was also a within-ear advantage, but its size was smaller being only 56 ms ($F\,(1, 37) = 6.43$, $P < 0.02$). As another way to conceptualize this interaction, the elongation of responses on the ordinal-decision task relative to the physical-identity task was substantially greater for within-ear trials (226 ms) than for across-field trials (137 ms) ($F\,(1, 37) = 11.42$, $P < 0.002$). This interaction was modified by a significant three-way interaction of ear of target by task by trial type ($F\,(1, 37) = 5.82$, $P < 0.03$). Tests of simple effects revealed that this interaction was driven by the ordinal-decision task ($F\,(1, 37) = 11.98$, $P < 0.002$). For the ordinal-decision task only, there was a within-ear advantage when the target was presented in the right ear, and neither a within- nor an across-ear advantage when the target was presented in the left ear. In contrast, for the physical-identity task, performance did not vary depending on which ear received the target for within- versus across-ear trials ($P = 0.81$).

2.3.2. IHI effects on ISI

Although the interaction of trial type by ISI did not reach significance ($P = 0.14$), the three-way interaction between task, trial type and ISI ($F\,(1, 37) = 7.89$, $P < 0.01$) did. In order to further examine this three-way interaction we conducted a separate ANOVA for each task with the same within-subjects factors described above. These analyses revealed that for the physical-identity task, the size of the within-ear advantage did not vary when the ISI was 100 ms (158 ms within-ear advantage) as opposed to 250 ms (132 within-ear advantage) ($F\,(1, 17) = 0.14$, $P = 0.72$). In contrast, for the ordinal-decision task, the significant within-ear advantage of 117 ms for the 250 ms ISI condition switched to a non-significant across-ear advantage (4 ms) for the shorter 100 ms ISI condition ($F\,(1, 20) = 22.85$, $P = 0.0001$) (Fig. 2). Thus, the time constraints put on processing by the shorter ISI between the target and two probes had a specific effect on the utility of IHI for the computationally more complex ordinal-decision task. This pattern of results suggests that the effects of computational complexity on IHI as manipulated by ISI are separable from complexity as manipulated by the number of steps required to reach a decision.

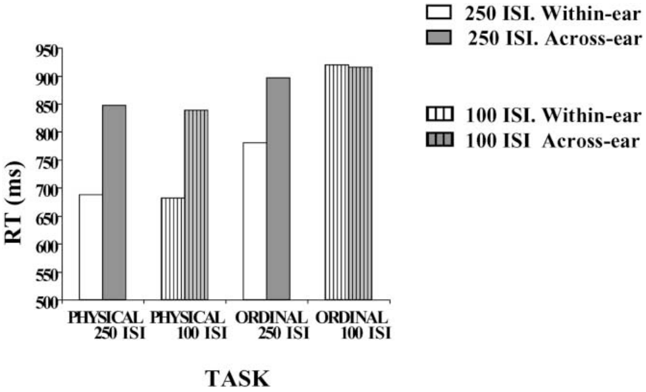

Fig. 2. Experiment 1: mean RT (ms) for within- and across-hemisphere trials for each condition (250, 100 ms ISI) and task (physical-identity, ordinal-decision).

Since mean RT varied significantly ($F\,(1, 37) = 29.23$, $P < 0.0001$) between the ordinal-decision task (921 ms) and the physical-identity task (739 ms) we wanted to make sure that our results were not an artifact of RT differences between the two tasks. Therefore, we transformed our data so that the within-ear advantage was calculated as a percentage of mean RT, using the following formula: (across-ear RT − within-ear RT)/((across-ear RT + within-ear RT)/2). We then conducted another ANOVA on this measure with the between-subjects factor of ISI and the within-subjects factors of task and ear of target. Importantly, the interaction of task by ISI was significant ($F\,(1, 37) = 9.94$, $P < 0.005$). In agreement with the pattern of results observed for the mean RT analysis, tests of simple effects revealed that for the physical-identity task, the size of the within-ear advantage did not vary depending on whether the ISI was 100 (21%) or 250 ms (18%). But for the ordinal-decision task, the within-ear advantage in the 250 ms ISI condition (13%) disappeared (0%) for the 100 ms ISI condition ($F\,(1, 37) = 5.48$, $P < 0.03$).

In conclusion, both the mean RT and the percent of mean RT analyses indicate that temporal constraints on processing selectively modulate IHI effects for the computationally more complex, ordinal-decision task.

2.4. Percent correct

2.4.1. IHI effects on task complexity

The main factor of ISI, which was not significant in the RT data was significant in the accuracy data ($F\,(1, 37) = 4.29$, $P < 0.05$). Accuracy was higher for the harder 100 ms ISI condition (0.88) than for the easier 250 ms ISI one (0.84). We believe that this effect reflects random variation in the assignment of participants to ISI conditions. It is important to note that this finding does not invalidate our definition of the physical-identity task as less complex, and the ordinal-decision task as more complex, since we define task complexity in terms of computational steps rather than on the basis of some general measure of difficulty, such as speed or accuracy.

As in the RT data, the main effects of trial type ($F(1, 37) = 6.14$, $P < 0.02$) and of task were significant ($F(1, 37) = 4.12$, $P < 0.05$), and both effects were modified by the significant interaction of task by trial type ($F(1, 37) = 5.79$, $P < 0.02$). Consistent with the RT data, tests of simple effects indicated that for the physical-identity task, accuracy on within-ear trials was significantly higher than on across-ear trials (0.90 and 0.85, respectively) ($F(1, 37) = 11.98$, $P < 0.002$). Different from the RT data, for the ordinal-decision task the within-ear advantage was not just reduced but disappeared, because accuracy did not differ for across- (0.84) and within-ear trials (0.84) ($F(1, 37) = 0.002$, $P = 0.97$). Finally, the three-way interaction between task, trial type and ISI, which was significant in the RT data, did not reach statistical significance here.

2.4.2. IHI effects on ISI

In agreement with our hypothesis that time constraints would modulate the effects of IHI on performance, the interaction of ISI by trial type, which missed significance ($P = 0.14$) in the RT data, was significant in the accuracy data ($F(1, 37) = 4.12$, $P < 0.05$). Tests of simple effects revealed that whereas the less complex 250 ms ISI condition yielded a significant within-ear advantage in accuracy ($F(1, 37) = 7.79$, $P < 0.01$), (within-ear trials = 0.87; across-ear trials = 0.81), this advantage disappeared for the 100 ms ISI condition (within-ear trials = 0.88; across-ear trials = 0.87). No evidence of speed-accuracy trade-offs was found in the data.[4]

2.5. Discussion

Section 2 demonstrated that in the auditory modality, as previously observed in the visual modality, within-hemisphere processing becomes relatively less efficient than across-hemisphere processing as computational complexity increases. In addition, increasing complexity by imposing temporal constraints on processing also increased the benefits of IHI on performance, but only for the more computationally-complex task.

We observed a within-ear advantage in the computationally easier physical-identity task both for RT and accuracy. Importantly, this within-ear advantage was reduced for the more complex ordinal-decision task. Hence, the results confirm that regardless of modality, as computational complexity increases by increasing the number of steps required to reach a decision, we see a shift away from an advantage of within-hemisphere processing towards across-hemisphere processing. The accuracy data strongly supported our hypothesis, in that the within-ear advantage for the less complex physical-identity task was totally eliminated for the more complex ordinal-decision task. In addition, for the more complex task, this within-ear advantage disappeared when processing was under tighter temporal constraints. These results indicate that increasing complexity by another means has the same effect, that of making within-hemisphere processing less advantageous.

It should be noted that although the exact pattern of within- and across-hemisphere advantage differs from those we obtained for the same tasks in the visual modality (e.g. experiment 2 in [7]), the shift towards a reduction in the advantages of within-hemisphere processing with increasing complexity is consistent across our studies. In the Banich and Belger study [7], for example, we found a within-hemisphere advantage for the physical-identity task, and a significant across-hemisphere advantage for the ordinal-decision task. In most, but not all [6] of our previous studies we have obtained a significant across-hemisphere advantage in RT for the computationally more complex condition. In contrast to that pattern, in the present study we did not find an across-hemisphere advantage for the more complex task. Rather, there was either a significant reduction in the within-ear advantage (RT data) or an absence of a within-ear advantage (accuracy data) for the more complex ordinal-decision task relative to the less complex physical-decision task. We suspect that this difference arises from the imposition of a time delay between the presentation of the target and the probes in our auditory paradigm, which is absent in our visual paradigm [7]. Hence, rather than having to process all three items simultaneously, as was the case in our visual version of the task, in the auditory task processing is distributed in time. As such, the overall level of complexity was reduced, and probably was not great enough to cause IHI to become significantly advantageous to performance. It might be that if we reduced the ISI between the presentation of the target and the probes even further, for example to 75 ms, we might find that across-hemisphere processing actually becomes advantageous to performance for the more complex task. Nonetheless, we do not consider this lack of across-hemisphere advantage problematic, because, the common pattern across all of our studies is a “relative shift” from within-processing

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[4] In a three-way ANOVA on d' scores we obtained similar results to the percent correct analysis, in that the within-ear advantage was reduced in the computationally more complex, ordinal decision task. Tests of simple effects on the significant interaction of task by trial type ($F(1, 37) = 4.55$, $P = 0.04$) showed that in the computationally easier physical-identity task, responses to within-ear trials (d' score = 2.62) were more accurate than to across-ear trials (d' score = 2.37) ($F(1, 37) = 8.82$, $P = 0.005$). On the contrary, in the computationally more complex ordinal-decision task, there was no difference between responses to across-ear trials (d' score = 2.29) and responses to within-ear trials (d' score = 2.31) ($F(1, 37) = 0.095$, $P = 0.76$). Finally, the interaction of ISI by trial type, which was significant in the percent correct analysis, was not significant here ($F(1, 37) = 0.2.97$, $P = 0.09$). A trend in the data shows that whereas with the longer ISI d' scores are higher for within- than for across-ear trials (d' score = 2.31 versus 2.08, respectively), with the shorter ISI this difference is greatly reduced (d' scores = 262 versus 258, respectively).

being more advantageous in simpler tasks to being less advantageous in more complex tasks. Fig. 2 illustrates this important theoretical point. This figure shows that when task complexity is relatively low (e.g. physical identity task) within-hemisphere processing is significantly more efficient than across-hemisphere processing, probably, because the advantage of greater computational power with IHI is outweighed by the cost of interhemispheric integration of information. Across-hemisphere processing is about as efficient for the less and the more complex tasks. But as we increase task demands by going from a physical identity to an ordinal-decision task, and by decreasing ISI from 250 to 100 ms, within-hemisphere processing is no longer more efficient than across-hemisphere processing.

We also would like to briefly discuss the fact that, different from previous studies, in the present one we found that IHI effects were dissociable for the left and right hemisphere only for the more complex task. Only for the ordinal-decision task there was a within-ear advantage when the target was received by the right ear (left hemisphere), and neither a within- nor an across-advantage when the target was received by the left ear (right hemisphere). Belger and Banich [11] found that the usual IHI advantage with complex tasks disappears in the visual modality when only one hemisphere is able to perform a specific type of processing (i.e. phonetic decision), most likely because a division of processes is not possible anymore. In our task both hemispheres should be able to make an ordinal-decision, but the left hemisphere may be superior to the right hemisphere in this type of processing because it can use more sophisticated symbolic strategies [24,26]. Hence, when ordinal-decisions are required for the left hemisphere, the costs of within-hemisphere processing are still lower than those of integrating information across-hemispheres. But for the right hemisphere, for which ordinal-decisions may be harder, the opposite may be true.

The second main goal of the present experiment was to determine whether IHI would also aid performance when complexity was manipulated in a manner that did not involve an increase in the number of steps required. This demonstration was important as manipulating the number of steps makes the assumption of pure insertion, and we wanted to show the relationship between task complexity and IHI in a manner that was free of this assumption. Consistent with our hypothesis, we found that increasing complexity by increasing temporal constraints made within-hemisphere processing less advantageous. The advantage for within-hemisphere processing was significantly greater for the 250 than the 100 ms ISI condition. Our pattern of results also suggests that the effects of task complexity as manipulated by the number of computational steps and by temporal constraints are somewhat separable. Yet, the effects are not completely additive, as a greater across-hemisphere advantage with the shorter ISI was only observed for the more complex ordinal task. For the computationally less complex physical-identity task, the RT advantage for within-ear processing remained constant regardless of ISI. Thus, the computations needed for a perceptual match did not seem to be much influenced by the time constraints imposed by the ISI. We speculate that the physical-identity task could be made on the basis of an echoic representation and both the ISIs we used provided enough time for such a representation to be formed, but not enough time for that representation to degrade. In contrast, for the ordinal-decision task the within-ear advantage observed with a 250 ms ISI disappeared with a 100 ms ISI. This finding suggest that providing 100 ms between the presentation of the target and the probes probably does not allow enough time for the relevant information about the target (i.e. its value) to be extracted in this task before the probes are presented. Hence, these findings suggest that the switch to an across-hemisphere advantage will only occur after a specific level of computational complexity has been reached, and that different manipulations of complexity (i.e. task requirements versus time requirements) can have separable effects. It is worth noting that the size of the within-ear advantage was not predicted by overall accuracy in the two tasks. Even though accuracy was higher overall for the 100 ms ISI condition, within-hemisphere processing was less advantageous for this condition than the 250 ms ISI condition. This result supports our claim that it is the computational requirements of the task that influence the effect of IHI, and not some overall index (such as mean RT or accuracy) of task difficulty. Such findings are in accord with those of Weissman and Banich [42].

Finally, the results of the current study also preliminarily address the question of whether the across-hemisphere advantage usually found for complex visual tasks is due to division of labor across the hemispheres [7] or to differences in the ability to transfer different types of representations across the hemispheres [31]. They suggest that the degree of computational complexity, rather than the nature of the representation, has the greatest influence on the utility of IHI. If the type of representation were the main factor driving whether or not IHI is helpful to performance, then ISI should have little effect on performance. In fact, the nature of the representation (i.e. an echoic one in this case) stays constant regardless of the particular ISIs between the probes and target that we utilized. Contrary to such a prediction, we observed that a reduction in ISI increased the benefits of IHI in the ordinal-decision task, even though the nature of the representation being transferred remained constant. Therefore our data suggest that the type of representation alone cannot explain why IHI is more advantageous under certain conditions than others. Rather, our data are consistent with our suggestion that the computational demands play a larger role in determining the effect of IHI on performance.

3. Experiment 2: effects of interhemispheric interaction on performance in the tactile modality

Our first experiment was successful in demonstrating that in the auditory modality, as has been previously observed in the visual modality, within-hemisphere processing becomes less advantageous as computationally complexity increases. The purpose of our second experiment was to determine whether this effect generalizes to the tactile modality as well. In order to do so, we once again adapted tasks from the visual modality [6,7]. In particular, we compared the effect of IHI on a physical-identity decision about shapes to that observed for a category-identity decision about the same types of stimuli [6,8]. In the physical-identity task, participants decided whether two geometric shapes were physically identical (e.g. "are these triangles identical?"). In the category-identity task, participants decided whether two shapes belonged to the same shape category (e.g. "are both these shapes triangles?" when a scalene and isosceles triangle are presented). As in the visual modality, participants compared two probe items to a target item. We varied whether the target and probe were directed to the same hemisphere (within-hemisphere trials) or to opposite hemispheres (across-hemisphere trials). However, some aspects of the task needed to be modified for the tactile modality. Whereas both probes were presented simultaneously in the visual modality, pilot work indicated that in the tactile modality this simultaneous presentation did not allow individuals to respond with a high level of accuracy. Thus, our tactile paradigm was more sequential in nature than either our visual or auditory paradigm, as each item was presented individually. In particular, participants felt the target, then the first probe and finally the second probe. As we have done in the visual modality, we wanted items to be directed to different sensory receptors on both within- and across-hemisphere trials (see [5] for discussion of this issue). Hence, on both within- and across-hand trials different fingers were always used to feel the target and the matching probe: the index finger and the fifth finger, respectively. We chose the index finger and the fifth finger as they do not share the same dermatome, which should reduce the possibility of interactions at the spinal level on within-hand trials. In the visual modality, the category-identity task is more complex than the physical-identity task, because in addition to perceptual processing of the form it requires at least the additional step of determining the category of each stimulus. But as we will explain below, the level of complexity for these two tasks is reversed in the tactile modality. As we did for our auditory task, we considered the particulars of somatosensory processing in reasoning about the computations required. With regard to our definition of task complexity, the most important change in our paradigm from the visual to the tactile modality was that of the sequential analysis, not only of each of the items, but of exploration of the items themselves. We found in pilot work that our participants could not just run their fingers over each tactile shape and determine what it was. Had they been skilled in reading Braille such a strategy might have been possible, but we found that accuracy was too low when participants were given only one pass over the shape. Rather, the task could only be performed with an acceptable degree of accuracy if participants took the time to run their fingers around the circumference of each shape, feeling the sides one at a time. This limitation influences how complex the category task is relative to the physical-identity task. In the tactile modality making a correct decision about category-identity requires the individual to decide if two shapes have the same number of sides (e.g. three versus four) and the same form (e.g. curved versus straight). However, the physical-identity task requires participants to perform the additional computation of deciding whether the lengths of each side of the shapes are identical as well, and to keep this information in working memory. Therefore the working memory load is increased for the physical-identity task as compared to the categorical one. Because the sequential strategy employed to both explore the items and make comparisons in the tactile modality is so different from the simultaneous processing possible in the visual modality, the relative computational difficulty varies between the two modalities. Unlike the visual modality, the physical-identity task is *more* computationally complex than the category-identity task in the tactile modality.

3.1. Methods

3.1.1. Participants

Our participants were 28 undergraduates enrolled at the University of Illinois at Urbana-Champaign. They were either compensated $8 for participating in this study or received class credit. All participants were right-handed, as assessed by a questionnaire that evaluated hand-preference for each of eight activities (such as using a spoon, using scissors, throwing a ball, etc.). Participants were considered right-handed if they wrote with their right hand and performed seven of the eight activities with their right hand. They reported no neurological impairment and normal manual and tactile functions. None of the individuals who participated in experiment 2 had participated in experiment 1.

3.1.2. Equipment

A steel chassis of 34 cm × 24 cm × 30 cm was used as a stage in which participants placed their arms. A blue non-transparent cloth (1.3 m × 0.91 m) placed on the steel chassis was used as a curtain to prevent participants from seeing the stimuli. An electronic timer was used to time the 5 s allotted for the tactile exploration of each of the three shapes on the sample card. The experimenter recorded participants' responses on an answer sheet.

3.1.3. Stimuli

We used the same stimuli as in Banich and Passarotti's study [8]. These stimuli consisted of 16 geometric shapes, divided in four categories (rectangles, triangles, ovals and diamonds) with four instances of each category. Compared to our visual version of this experiment, we enlarged the area of each shape (130%) to allow a better discrimination by touch of the borders of each shape, and to allow participants to run their fingers around each shape in a more comfortable manner. All the shapes were traced on 100-grit sandpaper and subtended an area of approximately 2 cm^2. We wanted all shapes to have the same area in order to ensure that participants would discriminate the features of the shapes independently of their surface area (e.g. a big rectangle would be easier to discriminate than a smaller triangle). These shapes were cut and pasted in triplets on 20 cm × 20 cm cardboard plates. The centers of the shapes were placed 3.5 cm equidistantly apart from each other on the cardboard. On half of the trials the target shape matched one of the other two shapes (match trials), and on the other half it did not (mismatch trials).

Similar to previous experiments in the visual modality [7,8,12] in this experiment half of the match trials required IHI (across-hand trials: the target shape felt with one index finger matches a probe shape felt with the fifth finger of the opposite hand) and half did not (the target shape felt with one index finger matches a probe shape felt with the fifth finger of the same hand) (Fig. 3a and b). We know that IHI is necessary to compare tactile information on across-hand trials, because of the robust experimental evidence that split-brain patients cannot compare objects felt with different hands (hemispheres) [19].

For both the within- and across-hand trials of the physical- (Fig. 3a) and the category-identity task (Fig. 3b), the target was felt with the left hand for half of the trials, and with the right hand for the other half. In this way, on each task we had four different match trial types, which occurred equally often: (1) within-right hand trials: the target and matching probe are felt with the right hand; (2) within-left hand trials: target and matching probe are felt with the left hand; (3) across-right hand trials: target felt with the right hand and matching probe felt with the left hand; (4) across-left hand trials: target felt with the left hand and matching probe felt with the right hand. Note that in this nomenclature, by "hand" (right or left) we indicate the hand that feels the target. Because the probes were felt serially one after the other, on half of the trials the left fifth finger would feel a probe first, and on the other half the right fifth finger would feel a probe first. This was true for both match and mismatch trials.

The nature of mismatch trials varied somewhat across tasks. In the physical-identity task there were three types of mismatch trials. Half of mismatch trials were mismatch same-category trials, in which the target and one probe belonged to the same shape category but were physically different (e.g. an equilateral and isosceles triangle). These trials were equally divided between those in which the items from the same category were presented to the same hand (mismatch same category within trials) and those in which the items from the same category were presented to opposite category (mismatch same category across trials). The remaining

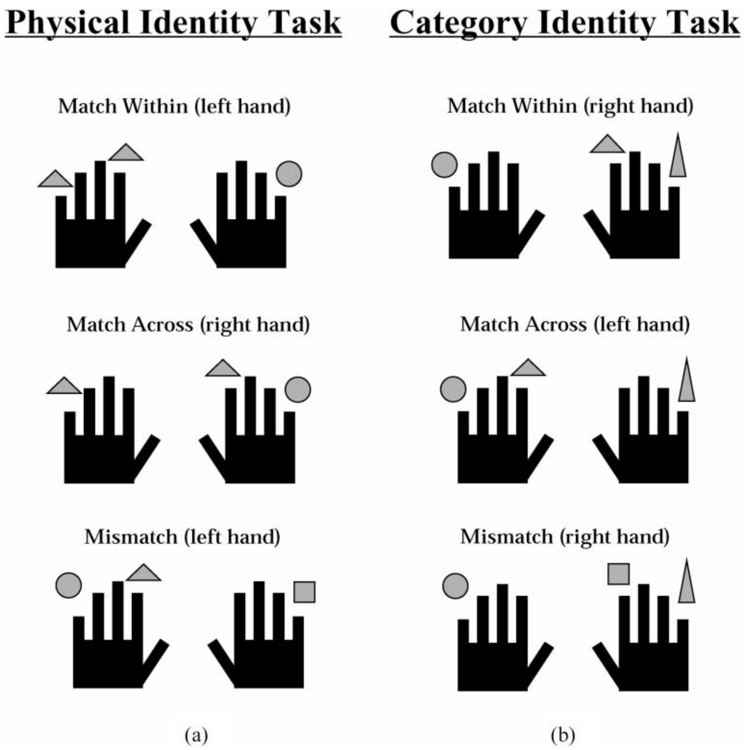

Fig. 3. Experiment 2: sample match and mismatch trials. Right hand trials are those on which the target (shown in the center) was felt by the right index finger, and left hand trials are those on which the target was felt by the left index finger. The probes depicted on either side of the target were felt by the fifth finger of each hand: (a) examples of the trial types for the physical-identity task; (b) examples of the trial types for the category-identity task. Different from the physical-identity task, in the category-identity task all mismatch trials are mismatch different category trials, as all the three items belong to different shape categories.

half of the mismatch trials were mismatch different-category trials, in which all the three items belonged to a different shape category (e.g. oval, rectangle, triangle). Within each of these subcategories, the target was presented to the left hand on half the trials and to the right hand on the other half. In the category-identity task, all mismatch trials were different category trials, as all three items belonged to different shape categories.

3.1.4. Procedures

We followed the same screening procedures as in Section 2, except that we replaced a check on basic auditory processing by one on basic somatosensory processing. To do so, we queried participants about whether they had dexterity problems, scars on their hands, or hobbies (e.g. playing an instrument) that might affect their tactile performance. If they did, they were excluded from participation. In addition, as in Section 2 participants performed the CFT [28], although we did not include results from this test in the present discussion.

After the screening, participants were introduced to the actual experimental session. In a 1–1/2 h session, participants performed the two experimental tasks (physical- and category-identity task). In each task they felt, in sequence for 5 s each, the target and then each of the two probes. They always felt the target with the index finger (either left or right) and each probe with the fifth finger (one probe by the left and one by the right). Before beginning each task, participants read the instructions and were encouraged to explore by touch a template card containing all of the 16 shapes used in the two tasks. On each task, participants performed eight practice trials, followed by two blocks of 16 trials each (for a total of 16 practice trials and 64 experimental trials). As in previous experiments [6,7], we always had participants perform the computationally easier task (in this study, the category-identity task) before the computationally more difficult task (in this study, the physical-identity task), because the computational steps necessary to perform the physical-identity task might have influenced the strategy used for the category-identity task. On the contrary, making a match according to category features would not enable the participants to reach a correct decision in the physical-identity task.

3.2. Results

For all 28 participants we calculated d' scores and accuracy rates for the physical- and category-identity tasks. We excluded four participants from our data analysis, because they had a d' score of less than 1.0 on at least one task. Therefore, our ANOVA on d' scores and accuracy were carried out on the remaining 24 participants. Since both the analysis on d' and that on accuracy led to the same results, we will present our data in terms of participants' accuracy (but see footnote No. 5 for corresponding d' analysis). The overall average accuracy on match trials was 84%. Our results are discussed first with regard to IHI effects on task complexity, and then with regard to hemispheric differences.

3.3. Percent correct

In order to examine the effects of IHI on the physical- and category-identity tasks, we performed a three-way repeated measures ANOVA on percent correct. There were three within-participants factors: task (physical-, category-identity), trial type (within-, across-hand), and index finger feeling the target (left, right). As in Section 2, we only analyzed match trials.

3.3.1. Effects of IHI on task complexity

The main effect of task was not significant ($P = 0.8$). With regard to our hypothesis that IHI would benefit performance more for the computationally more complex task than for the less complex one, the interaction of task by trial type ($F(1,23) = 2.37$, $P = 0.134$) did not reach conventional levels of significance. However, since we had a specific hypothesis about this interaction, we performed tests of simple effects. These revealed that in the computationally less complex category-identity task, responses to within-hand trials (0.88) were more accurate than to across-hand trials (0.80) ($F(1,23) = 5.52$, $P < 0.05$). In contrast, for the computationally more difficult physical-identity task, there was no significant difference between responses to across-hand trials (0.85) and responses to within-hand trials (0.84) ($F(1,23) = 0.14$, $P = 0.71$).[5]

3.3.2. Effects of hand differences on performance

With regard to hemispheric differences in task performance the only main effect that reached significance was the effect of index finger feeling the target ($F(1,23) = 8.16$, $P < 0.01$) This effect was modified by a significant interaction of task by index finger feeling the target ($F(1,23) = 9.05$, $P < 0.01$). Tests of simple effects revealed that when the left index finger (right hemisphere) felt the target, accuracy was superior on physical-identity trials (0.86) as compared to category-identity trials (0.75) ($F(1,23) = 4.3$, $P = 0.05$). On the contrary, when the right index finger (left hemisphere) was used to feel the target, accuracy was superior on category-identity trials (0.93) than on physical-identity trials (0.83) ($F(1,23) = 9.0$, $P < 0.01$). Tests of simple effects also revealed

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[5] Similar results to the percent correct analysis were obtained in a three-way ANOVA on d' scores, in that the within-hand advantage was reduced in the computationally more complex, physical-identity task. The interaction of task by trial type ($F(1,23) = 2.47$, $P = 0.13$) did not reach significance, but tests of simple effects revealed that in the computationally easier category-identity task, responses to within-hand trials (d' score $= 2.80$) were more accurate than to across-hand trials (d' score $= 2.43$) ($F(1,23) = 5.81$, $P < 0.05$). In the computationally more difficult physical-identity task, there was no significant difference between responses to across-hand trials (d' score $= 2.78$) and responses to within-hand trials (d' score $= 2.85$) ($F(1,23) = 0.10$, $P = 0.76$).

that hemispheric differences were only observed for the category-identity task, as accuracy was higher when the right index finger (left hemisphere) (0.93), rather than the left index (right hemisphere) (0.75), was used to feel the target ($F(1, 23) = 16.18$, $P = 0.001$). In contrast, for the physical-identity task, performance did not differ ($F(1, 23) = 0.43$, $P = 0.52$) when the target was felt by the left index (right hemisphere) (0.86) as compared to the right index finger (left hemisphere) (0.83). Finally, no significant interaction of trial type by index finger feeling the target was found, suggesting that in the present study hemispheric differences did not mediate IHI effects or vice versa.

3.4. Discussion

Our hypothesis that within-hemisphere processing would become relatively less efficient than across-hemisphere processing with increased computational complexity also received support in the tactile modality. Before discussing our IHI findings, we want to comment on the fact that we did not find a significant main effect of task. Although one might have expected the computationally more complex task to lead to less accurate performance, this was not the case. Nonetheless, this finding does not invalidate our claim that the physical-identity task is harder, since we base our metric of complexity on a computational analysis of the steps required to perform the task. In other studies, we have found that the effect of IHI on task performance cannot be explained by level of task difficulty as solely measured by reaction time or accuracy (see also [41]). Although the critical interaction of task by trial type did not reach significance, the pattern observed was similar to the one we predicted, with a trend for within-hemisphere processing becoming less advantageous as computational complexity increased. Our results may only have approached significance because of the sequential processing involved in having the participants feel each shape for 5 s. This methodology may have greatly decreased the amount of processing to be performed per time unit, diluting the beneficial effects that IHI has on task performance as complexity increases [10]. As illustrated by the results for Section 2, varying the temporal constraints on processing does affect the utility of interhemispheric processing.

Finally, although in our tactile task we obtained some asymmetry effects with regards to hand, they nonetheless did not interact with IHI effects. Tests of simple effects showed that the right hemisphere was more accurate for physical comparisons than categorical ones, whereas the opposite result held true for the left hemisphere. Our results agree with findings from neurologically intact individuals showing a left hand (right hemisphere) superiority when complex shapes must be felt and identified [43], and a right hand (left hemisphere) superiority for identification of letters drawn in the palm [33], and letters made of sandpaper [22].

4. General discussion

The aim of this paper was to determine whether within-hemisphere processing becomes less efficient than across-hemisphere processing as task complexity increases, regardless of the modality in which information is presented. The outcome of Section 2, and to a smaller extent the outcome of Section 3, supports such a generalization. Therefore we suggest that IHI is a general mechanism that the brain uses across different modalities (visual, auditory and tactile) to increase processing efficiency, most likely by splitting the load of processing between the two hemispheres and allowing information to be processed in parallel [8–10].

Another important feature of this study is that whereas previous ones [7,12] manipulated complexity in terms of the number of computational steps in a task, the present study replicated previous findings even when manipulating complexity in a different way, that is in terms of temporal constraints. In the auditory modality, for the more complex ordinal task, performance on within-hemisphere trials was superior to that of across-hemisphere trials when there was an ISI of 250 ms, but this advantage disappeared with an ISI of 100 ms. These results provide evidence for our hypothesis about IHI and computational complexity using a paradigm that does not depend on the assumption of “pure insertion”.

Our two experiments also demonstrate that the temporal distribution of information plays an important role in determining the effects of IHI on performance. In fact, longer processing times appear to diminish computational demands, thereby lessening the degree to which performance benefits from interhemispheric transfer of information. This conclusion is suggested both by the ISI effects that we found for the auditory modality (Section 2), and by our findings for the tactile modality (Section 3). Because processing was elongated in the temporal domain in the tactile task (by making processing more sequential in nature and giving participants 5 s to process each tactile shape), we no longer obtained an across-hemisphere advantage for the computationally more complex task.

As in the Belger and Banich study [11,12], we also found in the auditory modality separable effects of our two means of manipulating complexity (i.e. in terms of computational steps, and in terms of temporal constraints). Whereas the ISI manipulation did not affect performance for the physical-identity task, it did have an effect for the more complex ordinal-decision task. Not only was the within-hemisphere advantage reduced when more computations were necessary (i.e. the ordinal-decision task), it also disappeared as less time was given to process information (i.e. as occurred in the 100 ms as compared to 250 ms ISI condition).

As we pointed out in the discussion of each experiment, we did not obtain a significant across-hemisphere advantage for the more complex task in either the auditory or tactile tasks. What is important about our results, however, is that the *relative* advantage of within-hemisphere processing decreases as task complexity increases. Across our various studies, we have not always obtained a within-hemisphere advantage for the less complex task and an across-hemisphere advantage for the more complex task. What has been stable across experiments is that within-hemisphere processing is less advantageous for more complex tasks. We obtained such a pattern in the present experiment as well.

Lastly, although further studies will be needed to more directly address this issue, our present findings suggest that computational complexity of tasks, rather than the representation transferred callosally, predicted the utility of IHI. Although we cannot exclude that the nature of representation plays a role as proposed by Marsolek and colleagues for the visual modality, our results in non-visual modalities could not be explained solely by the nature of the representation, or else we would not have obtained a difference in the effects of IHI between the 250 and 100 ms ISI conditions in Section 2. These findings suggest that the type of representation involved in a task by itself is not enough to explain IHI effects, and that it is specifically the processing demands that will determine the degree to which IHI is beneficial to performance.

In addition, there are a number of studies in the visual modality performed in our laboratory that provide converging evidence to this interpretation. These studies yield a shift to an across-hemisphere advantage as task complexity increases, even when the type of representation in a task was held constant. For example, in a study requiring a color categorization decision [36], there was a shift from a within- to across-hemisphere advantage for the same category-identity task as we increased the difficulty of discrimination between colors. Similarly, in another physical-identity task in which subjects attended to shape while ignoring color [8] we produced a shift from within- to across-hemisphere processing as we increased the demands on selective attention. Notice that the representation that would need to be transferred is constant across the difficulty manipulation in both experiments. A representation of color information would need to be transferred in the former case, both when color discriminations were easy and hard. Likewise, a representation of shape information would need to be transferred, regardless of the nature of the distracting information. Hence, a theory positing that the nature of the representation being transferred influences the utility of interhemispheric processing would not have predicted differences in performance with computational demands.

In conclusion, we think that the importance of our present findings extends beyond the domain of IHI, to the cognitive neuroscience of attention. By considering the two hemispheres as relatively independent subsystems and studying their interactions across different modalities, we provide an operational model of how different brain areas may interact with each other to maximize the brain's processing capacity.

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