Potential Cross-modal Transfer Effects in Multisensory Integration Paradigms

Authors: calyx tube, Wenpei Luo, Han Jiahui, Han Jiahui

Date: 2021-12-20T00:00:00+00:00

Abstract

The brain can process and integrate information from different sensory modalities. Compared with a single sensory modality, individuals respond faster to target signals presented simultaneously across different sensory modalities. A major theoretical explanation for this phenomenon is the co-activation model, which posits that stimuli from different modalities converge and integrate in specific brain regions, such as the intraparietal sulcus, superior temporal sulcus, and prefrontal cortex. The integrated signal has greater intensity and can trigger responses more rapidly; however, at which stage of cognitive processing this integration occurs remains inconclusive. When individuals process task switches occurring between different sensory modalities, the cost of modality-related task switching is less than the sum of cross-modal switching cost and task switching cost, providing evidence that modality-related switch costs originate from inertia and interference in task-set configuration. However, when switching between single-modality and multi-modality conditions, the cross-modal switching cost is reduced or even eliminated, as simultaneous multisensory integration offsets part of the cost—a phenomenon that supports the co-activation model theory. Nevertheless, how multisensory signal integration influences the neural processing of task switching remains unclear. Future research could combine and refine multisensory integration paradigms with classical task-switching paradigms to determine the processing mechanisms of cross-modal switching and the stage at which multisensory signal integration occurs.

Full Text

Preamble

Affiliation

Key Laboratory of Brain and Cognitive Neuroscience, Liaoning Province, Dalian, 116029

The brain can process and integrate information from different sensory channels. Compared with single-modality stimulation, individuals respond faster to target signals presented simultaneously across different sensory modalities. A primary theoretical explanation for this phenomenon is the co-activation model, which posits that stimuli from different channels converge and integrate in specific brain regions such as the intraparietal sulcus, superior temporal sulcus, and prefrontal cortex. The integrated signal is stronger and can trigger responses more quickly, though the precise cognitive processing stage at which this integration occurs remains unclear. When individuals process task switches between different sensory modalities, the modality-specific switching cost is less than the sum of cross-modal switching cost and task switching cost, providing evidence that modality-related switching costs originate from inertia and interference in task set configuration. Moreover, when switching occurs between single-channel and multisensory conditions, the cross-modal switching cost is reduced or even eliminated because concurrent multisensory integration offsets part of the loss, a phenomenon that supports the co-activation model. However, how multisensory signal integration affects the neural processing of task switching remains unknown. Future research could combine the multisensory integration paradigm with the classic task-switching paradigm to determine the processing mechanisms of cross-modal switching and the stage at which multisensory signal integration occurs.

Keywords: multisensory integration, redundant signal effect, cross-modal switching effect, task switching

In daily life, the scenes and objects around us constantly change, requiring us to continuously switch from one context to another, and most of the information we receive comes from different sensory channels. Task switching refers to the process of shifting from the currently executed task to a new one, while processing and responding to received multisensory signals constitutes the multisensory integration process. When target signals are presented simultaneously across different sensory modalities, our response process accelerates. These multisensory signals are called redundant signals (Gondan & Minakata, 2016). People often use redundant signals to ensure information is accurately transmitted to the recipient—for instance, a police car’ s siren and flashing lights—eliciting faster and more accurate responses compared to single signals.

Received: July 12, 2021 * Corresponding author: Han Jiahui Tel./Fax: +86 411-82159796 E-mail addresses: jiahui110509@163.com; jiahui666@lnnu.edu.cn Funding information: National Natural Science Foundation Youth Project (32100848), Liaoning Provincial Natural Science Foundation Project (2020-BS-186), Liaoning Provincial Department of Education Project (LQ2020029), Liaoning Provincial Economic and Social Development Research Project

(2022lslwzzkt-025), Liaoning Normal University Doctoral Startup Project (BS2020L006).

Most information we receive in daily life enters the brain through different sensory channels. The brain can integrate stimuli from different sensory modalities and process this information in a unified manner—this processing is known as multisensory integration. Common methods for studying behavioral effects of multisensory integration involve simple rapid response time tasks, including rapid discrimination tasks and rapid detection tasks. Detection tasks require participants to respond as quickly as possible to all received stimuli, whereas rapid discrimination tasks require participants to identify predetermined target stimuli among received inputs and respond promptly. In rapid response time paradigms, participants are presented with either a single sensory channel stimulus (e.g., visual signal V alone or auditory signal A alone) or multiple different sensory channel stimuli simultaneously (e.g., visual signal V and auditory signal A presented together). As early as 1962, Hershenson conducted a classic experiment presenting participants with visual, auditory, and synchronous audiovisual stimuli, instructing them to respond upon seeing or hearing the target stimulus, and observed accelerated average response speed under simultaneous audiovisual conditions (Hershenson, 1962). Innes and Otto (2019) similarly confirmed in their experiments that participants responded faster to bimodal audiovisual signals than to visual or auditory signals alone, referring to simultaneously presented audiovisual stimuli as redundant signals. Shaw et al. (2020) utilized a rapid detection task paradigm to compare reaction time differences when participants responded to unisensory versus multisensory stimuli, demonstrating a facilitatory effect of multisensory stimulus signals. To date, substantial experimental evidence has shown that when using multisensory channel stimuli (redundant signals) to complete tasks, participants respond more accurately and quickly compared to single-channel stimuli (single signals). This response facilitation phenomenon is known as the redundant signals effect, or RSE (Gondan & Minakata, 2016). The RSE represents an important research topic in multisensory processing.

Recently, Barutchu and Spence (2021) used both detection and discrimination tasks to investigate the relationship between multisensory integration processing and stimulus specificity, employing auditory and visual forms of letters b and d presented in either single or dual sensory channels. In detection tasks, participants responded as quickly as possible to all stimuli, while in discrimination tasks, participants responded only when target letters (b or d) appeared. Results showed that in detection tasks, participants responded faster when visual and auditory stimuli were presented simultaneously; in discrimination tasks, the RSE occurred only when both visual and auditory stimuli matched the target letter, with slower responses when stimuli were incongruent with the target (Barutchu & Spence, 2021). The reason for this dissociation may be that Barutchu and Spence' s paradigm did not separate rapid response tasks from switching tasks, allowing the RSE to be influenced by switching costs. We will describe the relationship between these two effects in more detail in Section 3.

Researchers have proposed various theoretical models to explain this multisensory response facilitation effect, with the two most widely accepted being the "race model" and the "co-activation model." The race model (Miller, 1982) posits that when processing multisensory channel stimuli, each channel' s signal is processed independently, with multiple channels forming a competitive pattern. The response to redundant signals is determined by the competition winner (Figure 1 [Figure 1: see original paper]). Taking redundant signals composed of two channel stimuli as an example, the reaction time to each stimulus varies across trials, and the reaction time distributions of the two stimuli overlap. Competition between the two signals causes the overall average reaction time distribution to shift toward shorter times than either single-channel stimulus alone—this change is predictable because the redundant effect results from statistical facilitation (Raab, 1962). The co-activation model (Blurton et al., 2014) proposes that stimuli from different sensory channels converge and integrate at a specific processing stage, producing a signal stronger than any single-channel signal alone that reaches the sensory threshold more quickly to trigger a response, thereby generating the RSE (Figure 2 [Figure 2: see original paper]). Typically, response speed under the co-activation model is significantly faster than multisensory stimulus response speed under the race model (Maslovat et al., 2018).

Figure 1 (adapted from Raab, 1962) Race model. Stimuli from different channels S1 and S2 proceed independently; the response is activated by whichever stimulus arrives first. Competition leads to statistical facilitation of reaction time. S1 and S2 refer to stimulus signals from different channels; S(t) is the stimulus signal function over time.

Figure 2 (adapted from Raab, 1962) Co-activation model. Stimuli from different channels S1 and S2 converge and integrate in a specific region; the integrated signal strength exceeds that of single S1 or S2 stimuli, enabling faster response triggering.

To distinguish between race and co-activation processing models, Miller (1982) proposed the race model inequality (RSI), which has become a conventional method for testing behavioral data in RSE-related experiments:

$$P(RT \leq t|S1+S2) \leq P(RT \leq t|S1) + P(RT \leq t|S2) \quad (1)$$

The left side of the inequality represents the cumulative probability density distribution function of reaction times under redundant signal conditions, while the right side represents the cumulative probability density distribution functions of reaction times corresponding to single-channel input signals. S1 and S2 refer to two stimuli from different channels.

According to this formula, under race model conditions, the cumulative probability of reaction times to redundant signals is always equal to or lower than the probability distribution for single signals. When behavioral data violate this inequality, the race model is rejected in favor of the co-activation model. In existing validation experiments, most results have shown violations of the race model, thereby supporting the co-activation model hypothesis. The race model inequality assumes contextual independence of stimulus signals from two channels—that is, the reaction time distribution for each stimulus remains unchanged whether presented alone or simultaneously with another stimulus (in redundant signals).

Some researchers argue that when inequality (1) is violated, it may reflect either the co-activation model or a violation of contextual independence, producing contextual dependency (Miller, 2016). Contextual dependency refers to the phenomenon where processing of two stimuli in redundant signal conditions influences each other, differing from when stimuli are presented alone—for example, the presence of a visual signal somehow affects auditory signal activity, generating additional activation that influences reaction time to the auditory signal. However, this contextual dependency assumption does not contradict the co-activation model but rather supplements it. Therefore, when responses violate the race model, they are considered consistent with the co-activation model hypothesis.

The co-activation model supports the notion that redundant signals undergo integration during cognitive processing, accelerating response triggering time. However, no unified explanation exists regarding which specific processing stage this integration of different channel stimuli occurs. Some researchers believe integration occurs at the sensory stage, while others argue that co-activation occurs at later response stages such as response initiation or motor execution (Maslovat et al., 2018). Still others have proposed interactive models, suggesting that some processing stages involve the race model while others follow co-activation model activity (Miller, 2016). Determining the specific stages at which multisensory integration interactive models occur requires further research.

Most existing experimental studies on RSE have violated the race model inequality. Although a few studies support the race model, they remain controversial due to insufficient evidence, and cognitive neuroimaging evidence is even scarcer (Otto & Mamassian, 2017; Shaw et al., 2020; Van der Stoep et al., 2015). Therefore, the following section will focus on the neural mechanisms of the co-activation model.

Researchers propose that if the co-activation model holds, there should be brain regions specialized for processing multisensory information that are activated only when multiple sensory information is presented simultaneously. Based on this hypothesis, neuroimaging studies have identified brain regions that respond exclusively to multisensory channel information. Taking audiovisual redundant signal input as an example, the first cortical areas to process visual and auditory stimuli are primary visual cortex V1 and primary auditory cortex A1. After initial processing, signals enter higher cortical regions for more complete representation, particularly the superior temporal sulcus (STS), intraparietal sulcus (IPS), and prefrontal cortex (PFC) (Van Atteveldt et al., 2014). Therefore, multisensory information integration may occur in these higher cortical regions, a hypothesis confirmed by recent studies.

Regenbogen et al. (2017) conducted a stimulus discrimination experiment presenting participants with prepared visual and auditory stimuli (A, V, and AV stimuli presented randomly) requiring judgment responses. The researchers also controlled stimulus difficulty by presenting audiovisual stimuli at different levels of clarity. fMRI analysis confirmed that the intraparietal sulcus (IPS) exerts top-down control over information exchange between visual and auditory sensory regions (Regenbogen et al., 2017). Additionally, Stickel et al. (2019) used fMRI in a multisensory integration experiment to compare olfactory-visual and auditory-visual integration neural networks between autism spectrum disorder patients and healthy participants. In the olfactory-visual paradigm, participants were randomly presented with matching pleasant/unpleasant tastes and pictures in single-channel and multichannel formats, requiring evaluative responses. The auditory-visual paradigm used matching pleasant/unpleasant sounds and pictures with the same presentation format. Results showed that during multisensory integration, the intraparietal sulcus, medial frontal cortex, and inferior frontal cortex were additionally activated in both olfactory-visual and auditory-visual paradigms, confirming that multisensory integration processing occurs in these regions (Stickel et al., 2019). However, some studies provide evidence that interactions between different channel signals can occur even earlier, at the primary cortical processing stage (Keil & Senkowski, 2018), where signals from one sensory channel can influence the excitability level of another sensory channel. Furthermore, multisensory signal integration pathways have been identified in the thalamus and superior colliculus (Cappe et al., 2007). These brain region findings also provide evidence for future research on neural mechanisms related to multisensory modality switching.

The aforementioned brain regions must cooperate when processing multisensory stimuli, a process involving activation of various brain regions, functional connectivity between regions, and neural oscillatory activity across cortical areas. Synchronization of neural oscillatory activity between regions can facilitate cross-modal influences among auditory, visual, or tactile modalities (Bauer et al., 2020). Mercier et al. (2013) had epilepsy surgery patients perform detection tasks, finding that auditory stimuli enhanced phase resetting of neural oscillations in visual cortex, affecting visual stimulus processing (Mercier et al., 2013). In another study by the same team, participants received single or mixed visual and auditory stimuli while EEG data were recorded from auditory processing regions. Results showed that visual stimuli could reset oscillatory activity in δ (1-4 Hz) and (4-7 Hz) bands in auditory cortex. Additionally, α (8-12 Hz) and β (12-30 Hz) band oscillatory coherence under multisensory conditions was greater than the sum of single-sensory conditions (Mercier et al., 2015). Combined with Bastos et al.'s (2015) anatomical tracing results in non-human primates showing that slower oscillatory activity supports longer-distance coupling, multisensory effects in low-frequency bands (such as and α) are related to top-down feedback from higher-order cortical processing regions for multisensory integration. In contrast, enhanced coherence observed in high-frequency oscillatory activity (such as γ waves) reflects bottom-up stimulus processing. These findings demonstrate that cross-channel influences occur at early primary cortical processing stages, while multisensory stimuli cause greater local and faster inter-regional oscillatory phase synchronization resetting, with the strength of this reset associated with faster reaction times—that is, the RSE.

In daily life, to cope with constantly changing task scenarios, humans require advanced and complex cognitive control processes that enable flexible responses to achieve goals. Task switching is a commonly used experimental paradigm for exploring cognitive control mechanisms (Rogers & Monsell, 1995). Task switching typically includes processes such as task representation, task preparation, task selection, and task execution. In task-switching experiments, the task type in the current trial sometimes changes from the previous trial (switch condition) and sometimes remains the same (repeat condition). Researchers comparing participant performance between switch and repeat conditions have found a very stable cost in both reaction time and error rate, termed "switch cost." Explaining the nature of this phenomenon and discussing related neural mechanisms has been a central focus of task-switching research.

A mixed task block containing two task types includes both repeat and switch trials (e.g., an AABBAA sequence), whereas a single-task block requires participants to complete only one task type, including only repeat trials (e.g., AAA or BBB sequences). Comparing participant performance on repeat trials across these two block types reveals longer reaction times and lower accuracy in mixed task blocks, a cost known as mixing cost.

In cued task-switching paradigms, varying the time interval between cue and target stimuli (i.e., preparation time) affects switch cost, with longer preparation times typically reducing switch cost, a phenomenon known as the preparation effect. However, extending preparation time does not completely eliminate switch cost; studies have shown that even with preparation times of 5 seconds or longer, substantial residual switch costs remain, termed the residual effect (Sohn et al., 2000).

The prefrontal cortex (PFC) is an important brain region involved in task-switching processes. Dove et al. (2000) used functional magnetic resonance imaging to investigate a letter judgment switching task, finding additional PFC activation under task-switching conditions. The PFC participates top-down in task processing and control, forming the basis for task representation, selection, preparation, and switching. For example, activation in bilateral dorsolateral PFC regions can be observed according to different task cues, and inferior temporal cortex activity related to task processing is also modulated by PFC activity. When task stimuli are ambiguous, requiring participants to make different response type choices and potentially make errors, the medial frontal anterior cingulate cortex (ACC) is activated to resolve stimulus-induced conflict (Dosenbach et al., 2007).

Additionally, Sohn et al. (2000) used fMRI to demonstrate that parietal regions are activated during task switching—for example, the intraparietal sulcus region is more active during switch tasks. Their results also suggest functional segregation within parietal regions: the posterior parietal region is more active when switching between task-relevant dimensions, while the anterior parietal region is more active when switching between stimulus-response mapping rules (Sohn et al., 2000). Beyond the aforementioned frontal and parietal regions, studies have identified many other brain regions that are more active during task switching than during task repetition, such as the cerebellum and various temporo-occipital cortex regions (Proskovec et al., 2019). In summary, task switching requires integrating various perceptual, attentional, memory, and motor processes, leading researchers to increasingly focus on identifying and understanding functional connections between different brain regions during task switching.

In general task-switching paradigms (where switching occurs only between single-channel stimuli), ERP results from task-switching experiments undergo time-frequency transformation to analyze oscillatory changes across different frequency bands in frontoparietal regions, investigating neural processing mechanisms involved in task switching. Many related studies show (Cooper et al., 2016; Wu et al., 2015) that compared with repeat trials, α-band oscillations in frontoparietal regions show significant decreases under switch conditions (switch effect). Similarly, compared with single repeat tasks, α-band oscillation strength significantly decreases in repeat trials within mixed tasks (mixing effect), consistent with the behavioral results mentioned above. Moreover, mixing effect differences occur earlier and are more persistent than oscillatory differences caused by switch effects, confirming that switch cost and mixing cost are related to transient and sustained cognitive control mechanisms, respectively (Capizzi et al., 2020).

The functional significance of α-band oscillatory activity in task switching is generally believed to activate an inhibitory top-down cognitive control mechanism. Specifically, when a new task set competes with the current task set, α-wave oscillatory activity can suppress attentional distraction and facilitate responses to the current task (Foxe et al., 2014). β-band oscillatory change patterns are consistent with α-band patterns, also showing mixing and switch effects (Capizzi et al., 2020). That is, β-wave oscillation strength significantly decreases under switch conditions in mixed tasks; comparing repeat trials in mixed tasks with those in pure repeat tasks shows similarly decreased β-wave oscillation strength, with mixing effects larger than switch effects.

However, the function of β oscillations in task switching has not been fully resolved. Cooper et al. (2019) argued that β oscillations during task switching are primarily related to sensorimotor functions (such as motor execution and preparation), but Capizzi et al. (2020) countered this view, suggesting that β-wave oscillatory changes during task switching reflect involvement of non-motor processes because β oscillatory brain region distribution is not limited to sensorimotor cortex areas. This conclusion has also found support in recent research (Spitzer & Haegens, 2017), showing that non-motor region β oscillations are related to many cognitive processes such as working memory, long-term memory, and decision-making. Therefore, we believe that, similar to α waves, β-wave neural oscillatory activity also reflects top-down processing mechanisms in the brain.

-band oscillatory changes differ from α and β bands, with -wave oscillation strength significantly increasing under switch conditions compared with repeat trials, showing a clear switch effect. A recent study also indicated that increased -wave activity strength in frontoparietal regions is inversely proportional to switch cost, representing efficient cognitive control (Cooper et al., 2017). These results suggest that -wave oscillatory activity is sensitive to switch cost and plays an important role in task-switching mechanisms (Capizzi et al., 2020). Combined with these findings, we hypothesize that -band oscillatory activity may be related to attentional shifting. When the current task differs from the previous one, participants need to shift attention to new relevant stimuli and establish a new task set, so greater -wave oscillation strength reflects more flexible attentional shifting ability. However, the relationship between -wave oscillatory activity and mixing effects has not yet received stable and clear evidence support, and its specific functional significance in task-switching processes requires more research evidence.

To address the aforementioned issues regarding the source of cross-modal switching costs and the stage at which co-activation occurs, we propose improvements to existing task-switching and multisensory response paradigms. First, combine the RSE research paradigm with the classic task-switching paradigm—for example, using two tasks such as judging number parity or magnitude, where each number stimulus is presented in picture (V) and audio (A) formats, with stimulus presentation modalities including A-A-A···, V-V-V···, AV-AV-AV···, with each block containing both task repeat and switch conditions. By comparing RSE magnitude under repeat versus switch conditions, we can analyze how switch effects influence the redundant signals effect. Second, add cross-modal switch conditions to single-channel task-switching paradigms—for example, presenting number stimuli randomly in visual and auditory forms so that switching can occur between modalities, within modalities, or both simultaneously. By comparing differences in brain region activation location and intensity when both types of switching occur versus when they occur separately, we can further localize the shared cognitive processing centers for both switching processes.

Furthermore, whether cross-modal switching costs result from changes in neural circuits or from top-down cognitive processing shifts remains unresolved. To determine the source of cross-modal switching costs, experiments could add stimuli requiring additional cognitive processing—such as numbers, text, or pictures with different meanings—to compare with meaningless audio or graphics used in classic RSE studies. Finally, current cross-modal switching research has focused primarily on auditory and visual channels; whether stable cross-modal switching costs and RSE facilitation can be observed when redundant signals combine auditory or visual channels with other sensory modalities (such as olfactory or tactile) requires further investigation.

References

Shi, Y., & Zhou, X. (2004). An important paradigm for executive control research—task switching. *Advances in Psychological Science*, 12(5), 672-679.

Sun, Y., Hu, Z., Zhang, R., Xun, M., Liu, Q., & Zhang, Q. (2011). Discussion on influencing factors in multisensory integration measurement paradigms. *Acta Psychologica Sinica*, 43(11), 1239-1246. https://doi:10.3724/SP.J.1041.2011.01239

Barutchu, A., & Spence, C. (2021). Top-down task-specific determinants of multisensory motor reaction time enhancements and sensory switch costs. *Experimental Brain Research*, 239(3), 1021-1034. https://doi.org/10.1007/s00221-020-06014-3

Bastos, A. M., Vezoli, J., Bosman, C. A., Schoffelen, J. M., Oostenveld, R., Dowdall, J. R., . . . Fries, P. (2015). Visual areas exert feedforward and feedback influences through distinct frequency channels. *Neuron*, 85(2), 390-401. http://dx.doi.org/10.1016/j.neuron.2014.12.018

Bauer, A. R., Debener, S., & Nobre, A. C. (2020). Synchronisation of Neural Oscillations and Cross-modal Influences. *Trends in Cognitive Sciences*, 24(6), 481-495. https://doi.org/10.1016/j.tics.2020.03.003

Blurton, S. P., Greenlee, M. W., & Gondan, M. (2014). Multisensory processing of redundant information in go/no-choice responses. *Attention Perception & Psychophysics*, 76(4), 1212-1233. https://doi.org/10.3758/s13414-014-0644-0

Capizzi, M., Ambrosini, E., Arbula, S., & Vallesi, A. (2020). Brain oscillatory activity associated with switch and mixing costs during reactive control. *Psychophysiology*, 57(11), Article e13642. https://doi.org/10.1111/psyp.13642

Cappe, C., Morel, A., & Rouiller, E. M. (2007). Thalamocortical and the dual pattern of corticothalamic projections the posterior parietal cortex in macaque monkeys. *Neuroscience*, 146(3), 1371-1387. https://doi.org/10.1016/j.neuroscience.2007.02.033

Cooper, P. S., Darriba, A., Karayanidis, F., & Barcelo, F. (2016). Contextually sensitive power changes across multiple frequency bands underpin cognitive control. *Neuroimage*, https://doi.org/10.1016/j.neuroimage.2016.03.010

Cooper, P. S., Karayanidis, F., McKewen, M., McLellan-Hall, S., Wong, A. S. W., Skippen, P., & Cavanagh, J. F. (2019). Frontal theta predicts specific cognitive control-induced behavioural changes beyond general reaction time slowing. *Neuroimage*, 189, 130-140. https://doi.org/10.1016/j.neuroimage.2019.01.022

Cooper, P. S., Wong, A. S. W., McKewen, M., Michie, P. T., & Karayanidis, F. (2017). Frontoparietal theta oscillations during proactive control are associated with goal-updating and reduced behavioral variability. *Biological Psychology*, 129, 253–264. http://dx.doi.org/10.1016/j.biopsycho.2017.09.008

Dosenbach, N. U. F., Fair, D. A., & Miezin, F. M. (2007). Distinct brain networks for adaptive and stable task control in humans. *Proceedings of the National Academy of Sciences of the United States of America*, 104(26), 11073-11078. https://doi.org/10.1073/pnas.0704320104

Dove, A., Pollmann, S., Schubert, T., Wiggins, C. J., & Yves von Cramon, D. (2000). Prefrontal cortex activation in task switching: An event-related fMRI study. *Cognitive Brain Research*, 9(1), 103-109. https://doi.org/10.1016/s0926-6410(99)00029-4

Elkhetali, A. S., Fleming, L. L., Vaden, R. J., Nenert, R., Mendle, J. E., & Visscher, K. M. (2019). Background connectivity between frontal and sensory cortex depends on task state, independent of stimulus modality. *Neuroimage*, 184, 790–800. https://doi.org/10.1016/j.neuroimage.2018.09.040

Foxe, J. J., Murphy, J. W., & De Sanctis, P. (2014). Throwing out the rules: Anticipatory alpha-band oscillatory attention mechanisms during task-set reconfigurations. *European Journal of Neuroscience*, 39(11), 1960–1972. https://doi.org/10.1111/ejn.12577

Gondan, M., & Minakata, K. (2016). A tutorial on testing the race model inequality. *Attention Perception & Psychophysics*, 78(3), 723-735. https://doi.org/10.3758/s13414-015-1018-y

Hershenson, M. (1962). Reaction time as a measure of intersensory facilitation. *Journal of Experimental Psychology*, 63(3), 289-293. https://doi.org/10.1037/h0039516

Innes, B. R., & Otto, T. U. (2019). A comparative analysis of response times shows that multisensory benefits and interactions are not equivalent. *Scientific Reports*, 9(1), 2921. https://doi.org/10.1038/s41598-019-39924-

Keil, J., & Senkowski, D. (2018). Neural Oscillations Orchestrate Multisensory Processing. *The Neuroscientist*, 24(6), 609–626. https://doi.org/10.1177/1073858418755352

Maslovat, D., Hajj, J., & Carlsen, A. N. (2018). Coactivation of response initiation processes with redundant signals. *Neuroscience Letters*, 675, 7–11. https://doi.org/10.1016/j.neulet.2018.03.029

Mercier, M. R., Foxe, J. J., Fiebelkorn, I. C., Butler, J. S., Schwartz, T. H., & Molholm, S. (2013). Auditory-driven phase reset in visual cortex: Human electrocorticography reveals mechanisms of early multisensory integration. *Neuroimage*, 79, 19–29. https://doi.org/10.1016/j.neuroimage.2013.04.060

Mercier, M. R., Molholm, S., Fiebelkorn, I. C., Butler, J. S., Schwartz, T. H., & Foxe, J. J. (2015). Neuro-oscillatory phase alignment drives speeded multisensory response times: An electro-corticographic investigation. *The Journal of Neuroscience*, 35(22), 8546–8557. https://doi.org/10.1523/JNEUROSCI.4527-14.2015

Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, 14, 247–279. https://doi.org/10.1016/0010-0285(82)90010-x

Miller, J. (2016). Statistical facilitation and the redundant signals effect: What are race and coactivation models? *Attention Perception & Psychophysics*, 78(2), 516–519. https://doi.org/10.3758/s13414-015-1017-z

Otto, T. U., & Mamassian, P. (2017). Multisensory Decisions: the Test of a Race Model, Its Logic, and Power. *Multisensory Research*, 30(1), 1–24. https://doi.org/10.1163/22134808-00002541

Peng, A., Kirkham, N. Z., & Mareschal, D. (2018). Information processes of task-switching and modality-shifting across development. *PLOS ONE*, 13(6), Article e0198870. https://doi.org/10.1371/journal.pone.0198870

Proskovec, A. L., Wiesman, A. I., & Wilson, T. W. (2019). The strength of alpha and gamma oscillations predicts behavioral switch costs. *Neuroimage*, 188, 274–281. https://doi.org/10.1016/j.neuroimage.2018.12.016

Raab, D. H. (1962). Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences*, 24, 574–590. https://doi.org/10.1111/j.2164-0947.1962.tb01433.x

Regenbogen, C., Seubert, J., Johansson, E., Finkelmeyer, A., Andersson, P., & Lundstrom, J. N. (2018). The intraparietal sulcus governs multisensory integration of audiovisual information based on task difficulty. *Human Brain Mapping*, 39(3), 1313–1326. https://doi.org/10.1002/hbm.23918

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, 124(2), 207–231. https://doi.org/10.1037/0096-3445.124.2.207

Sandhu, R., & Dyson, B. J. (2013). Modality and task switching interactions using bi-modal and bivalent stimuli. *Brain and Cognition*, 82(1), 90-99. http://dx.doi.org/10.1016/j.bandc.2013.02.011

Shaw, L. H., Freedman, E. G., Crosse, M. J., Nicholas, E., Chen, A. M., Braiman, M. S., . . . Foxe, J. J. (2020). Operating in a Multisensory Context: Assessing the Interplay Between Multisensory Reaction Time Facilitation Inter-sensory Task-switching Effects. *Neuroscience*, https://doi.org/10.1016/j.neuroscience.2020.04.013

Sohn, M.-H., Ursu, S., Anderson, J. R., Stenger, V. A., & Carter, C. S. (2000). The role of prefrontal cortex and posterior parietal cortex in task switching. *Proceedings of the National Academy of Sciences of the United States of America*, 97(24), 13448–13453. https://doi.org/10.1073/pnas.240460497

Spence, C., Nicholls, M. E. R., & Driver, J. (2001). The cost of expecting events in the wrong sensory modality. *Perception & Psychophysics*, 63(2), 330-336. https://doi.org/10.3758/bf03194473

Spitzer, B., & Haegens, S. (2017). Beyond the Status Quo: A Role for Beta Oscillations in Endogenous Content (Re)Activation. *Eneuro*, 4(4), Article e0170-17. http://dx.doi.org/10.1523/ENEURO.0170-17.2017

Stickel, S., Weismann, P., Kellermann, T., Regenbogen, C., Habel, U., Freiherr, J., & Chechko, N. (2019). Audio-visual and olfactory-visual integration in healthy participants and subjects with autism spectrum disorder. *Human Brain Mapping*, 40(15), 4470–4486. https://doi.org/10.1002/hbm.24715

Van Atteveldt, N., Murray, M. M., Thut, G., & Schroeder, C. E. (2014). Multisensory integration: Flexible use of general operations. *Neuron*, 81(6), 1240–1253. http://dx.doi.org/10.1016/j.neuron.2014.02.044

Van der Stoep, N., Spence, C., Nijboer, T. C., & Van der Stigchel, S. (2015). On the relative contributions of multisensory integration and crossmodal exogenous spatial attention to multisensory response enhancement. *Acta Psychologica*, 162, 20–28. http://dx.doi.org/10.1016/j.actpsy.2015.09.010

Wu, S., Hitchman, G., Tan, J., Zhao, Y., Tang, D., Wang, L., & Chen, A. (2015). The neural dynamic mechanisms of asymmetric switch costs in a combined Stroop-task-switching paradigm. *Scientific Reports*, 5, 10240. https://doi.org/10.1038/srep10240

The Modality Shifting Effects in the Multisensory Integration Paradigm

GUAN Lei $%#&, LUO Wenpei $, HAN Jiahui

[1]Research Center of Brain and Cognitive Neuroscience, Liaoning Normal University, Dalian 116029, China [2]Key Laboratory of Brain and Cognitive Neuroscience, Liaoning Province, Dalian 116029, China

Abstract

The signals from different sensory channels could be integrated and processed in the brain. Compared with stimulus from a single sensory modality, the individual responses were faster for the multisensory target signals. One theory explaining this phenomenon is the co-activation model. According to the co-activation model, the signals input through multiple sensory channels would be integrated in specialized brain regions, such as the intraparietal sulcus, superior temporal sulcus, and prefrontal lobe regions. The strength of the integrated signal is stronger, which could trigger the reaction more quickly. However, the integration of the multisensory signals has not been concluded to occur in which phase of the cognitive processing. When the task is switched between different modalities, the cost of task switching associated with the cross-modal is less than the sum of the modality switching cost and the single task switching cost, which provides evidence for the hypothesis that the switching cost associated with different sensory channels are derived from inertia and interference of the task set. Moreover, when modality switching occurs between single-modal and multi-sensory, the modality switching cost will reduce even disappear, which is due to the multisensory integration offset a part of loss. This supports the co-activation model. However, it’ s unknown how the multi-sensory integration affects the nerve processing of the task switch. We could try to solve it by combining the multisensory integration research paradigm with the classic task switching paradigm, further to determine the processing mechanism of the cross-modal shift and the processing phase of multisensory integration.

Keywords: multisensory integration, redundant signal effect, modality shift effect, task switching

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.