Dynamic Causal Modeling on the Identification of Interacting Networks in the Brain: A Systematic Review

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***Abstract*— Dynamic causal modeling (DCM) has long been used to characterize effective connectivity within networks of distributed neuronal responses. Previous reviews have highlighted the understanding of the conceptual basis behind DCM and its variants from different aspects. However, no detailed summary or classification research on the task-related effective connectivity of various brain regions has been made formally available so far, and there is also a lack of application analysis of DCM for hemodynamic and electrophysiological measurements. This review aims to analyze the effective connectivity of different brain regions using DCM for different measurement data. We found that, in general, most studies focused on the networks between different cortical regions, and the research on the networks between other deep subcortical nuclei or between them and the cerebral cortex are receiving increasing attention, but far from the same scale. Our analysis also reveals a clear bias towards some task types. Based on these results, we identify and discuss several promising research directions that may help the community to attain a clear understanding of the brain network interactions under different tasks.**

***Index Terms*— DCM, interacting networks, effective connectivity, brain regions.**

Abbreviations

DCM:	dynamic causal modeling.
fMRI:	functional magnetic resonance imaging.
EEG:	electroencephalography.
fNIRS:	functional near-infrared spectroscopy.
CNKI:	China knowledge resource integrated database.
CC:	cerebral cortex.
FC:	frontal cortex.
PC:	parietal cortex.
OC:	occipital cortex.
TC:	temporal cortex.
INS:	insula.
HPC:	hippocampus.
AMY:	amygdala.
BG:	basal ganglia.
Thal:	thalamus.
ACC:	anterior cingulate cortex.
CPM:	continuous passive movement.
DMN:	default mode network.
AM:	autobiographical memories.
EmpaToM:	empathy & Theory of Mind.

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I. Introduction

DYNAMIC causal modeling (DCM) is a generic Bayesian framework for inferring hidden neuronal states from brain activity measurements and their context-dependent modulation. Since its introduction in 2003 by Friston *et al.* [1] for functional magnetic resonance imaging (fMRI) data, following a dozen years of research involving hundreds of studies on dynamic changes among multiple brain regions, a consensus view has emerged suggesting that DCM is the predominant way of characterizing effective connectivity within networks of distributed neuronal responses [2]. Currently, DCM has been extended to the data of electroencephalography (EEG) [3] and functional near-infrared spectroscopy (fNIRS) [4]. The basic idea of DCM is to construct a reasonably realistic neuronal model of interacting brain regions, and enable effective connectivity among different brain regions to be estimated from observed data [1]. Previous reviews have highlighted the understanding of conceptual basis behind DCM and its variants from methodological [5], biophysical [6] and mathematical [7] aspects. However, no detailed summary or classification research on the task-related effective connectivity of various brain regions has been made formally available so far, and there is also a lack of application analysis of DCM for hemodynamic and electrophysiological measurements. Fortunately, the scientific literature has produced hundreds of studies that focused, directly or indirectly, on the application of DCM, which has resulted in a multitude of cases of the interactions between the elements of the interested neural system related to the different tasks. A comprehensive analysis for the effective connectivity of different brain regions using DCM for different measurement data is therefore eagerly anticipated. In line with this objective, this review aims to screen and fix on the most relevant DCM research available in the literature to identify the effective connectivity of various brain regions for different tasks. We focus on interacting networks in the brain under the conditions of tasks related to motor, cognition, and specific diseases. We screened more than six hundred papers in the past ten years and resulted in a total of 181 relevant publications. We structured our analysis to address three main research questions:

- What tasks are involved in the study on the identification of interacting brain networks using DCM?
- Which effective connectivity has been identified in these studies?
- What is the status of the three data sources used for brain connectivity analysis?

The rest of this article is organized as follows. In Section II, we describe the literature search methodology, which includes the search query, the exclusion criteria, and the taxonomy used to classify results by task types and effective connectivity. Then in Section III, the results of our analysis are reported and the most relevant trends are identified. In Section IV we present a critical analysis of the results and addressing the research questions posed. Finally, Section V concludes this article.

II. Materials and Methods

We obtained 673 titles from an initial search of the Web of Science database and China Knowledge Resource Integrated Database (CNKI) using the following query string on the paper title, keywords, and abstract, on papers published in the past decade (between 01-01-2011 and 31-12-2020):

(DCM OR "dynamic causal mode∗") AND ("effective connectivity" OR "brain network") AND (fMRI OR "functional magnetic resonance imaging" OR EEG OR electroencephalography OR fNIRS OR "functional near-infrared spectroscopy" OR NIRS OR "near-infrared spectroscopy" OR "optical topography")

After reading titles and abstracts, we excluded duplicated publications and those that met one or more of the following criteria: reviews, conference proceedings, book chapters, or dissertations; the studies include measurement data other than fMRI, EEG, or fNIRS; the studies include approaches other than DCM; DCM theory research, non-relevant primary outcome; subjects in research are not human. After reading the full texts a total of 181 papers were included in the study. The detailed selection process is illustrated in Fig. 1.

We classified the papers using a twofold taxonomy composed of effective connectivity and task categories, as shown in Fig. 2. According to traditional brain regions, effective connectivity has been grouped into the following six categories:

- Cerebral cortex (CC)-CC, which represented in the CC including frontal cortex (FC), parietal cortex (PC), occipital cortex (OC), temporal cortex (TC), insula (INS), and hippocampus (HPC), there are connections between certain two brain regions.
- CC- amygdala (AMY), which represented there are connections between CC and AMY.

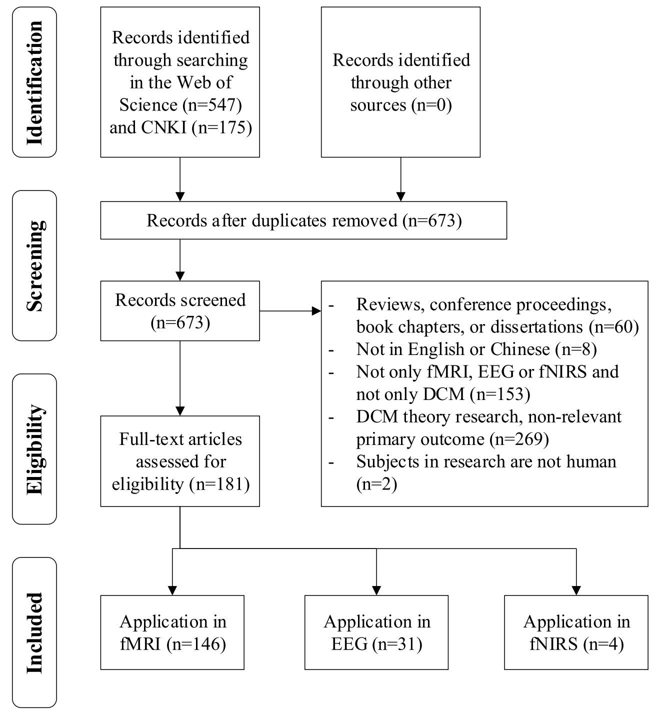

Fig. 1. PRISMA flow diagram of literature search.

- CC- basal ganglia (BG), which represented there are connections between CC and BG.
- CC-thalamus (Thal), which represented there are connections between CC and Thal.
- AMY-Thal, which represented there are connections between AMY and Thal.
- BG-Thal, which represented there are connections between BG and Thal.

Based on the types involved in all publications, the tasks were clustered into:

- Motor tasks, which included movement or motor-imagery of upper limb, lower limb and all four limbs.
- Cognitive tasks, which included multiple senses, working memory, emotion regulation, speech activities, decision-making and other cognitive tasks.
- Disease-related tasks, which included disease diagnosis and drug effect.

In addition, we further analyzed these papers based on different data sources. Considering that the COVID-19, we excluded the data for 2020, and some categories with too few numbers have not been included.

III. Results

Generally, as shown in Fig. 3, the number of publications has increased over the years although it has declined since 2016. However, the trends of different effective connectivity categories are diverse (Fig. 4). For instance, research on the interactions between CC and CC shows a growth similar to the overall trend. CC-AMY also rises on the whole, but with large fluctuations and low fit trend line. Other studies, including CC-BG, CC-Thal, AMY-Thal, and BG-Thal, were

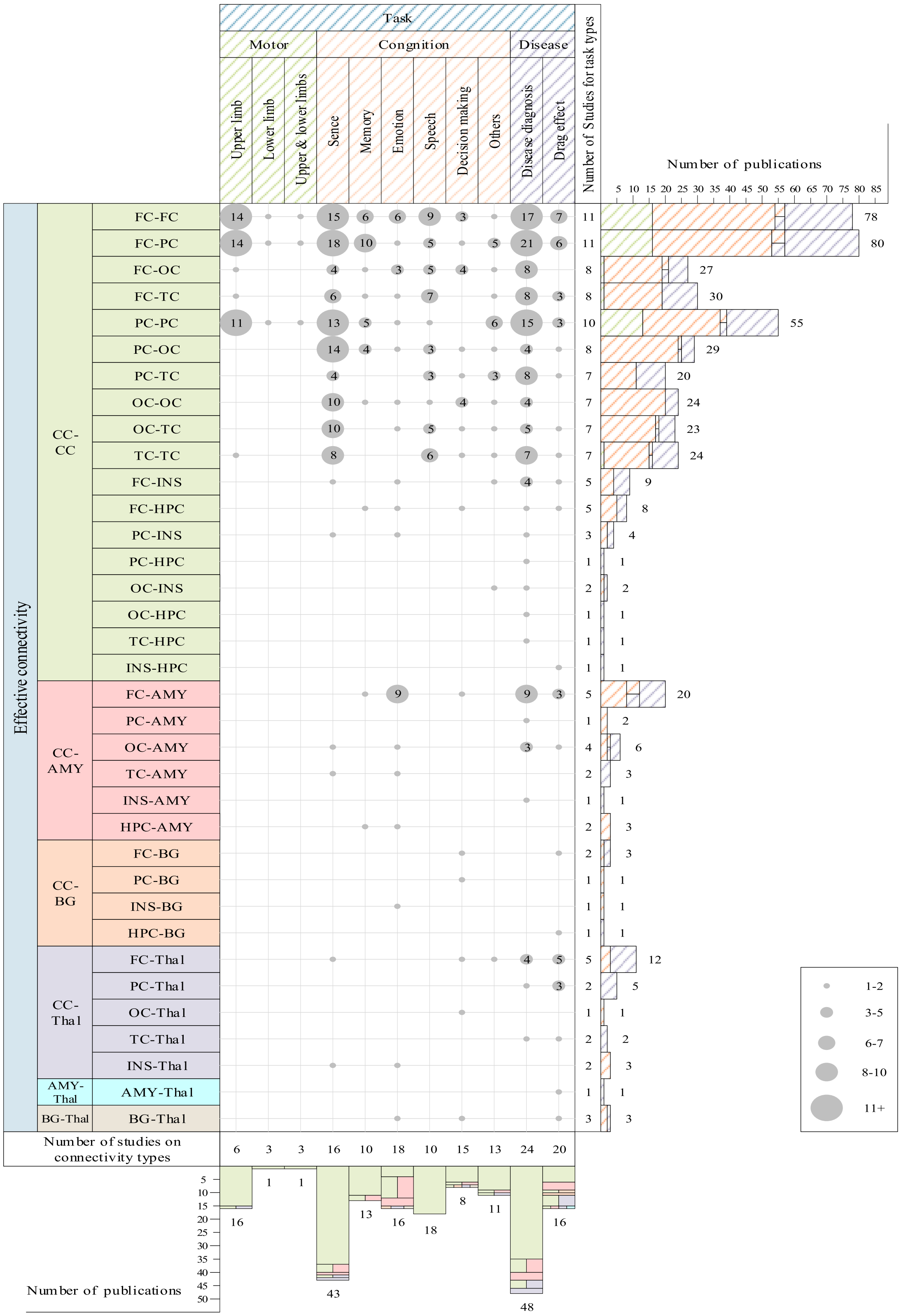

Fig. 2. Taxonomic overview of the reviewed studies. The size of the grey dot represents the number of reviewed studies.

not further analyzed due to the small number (1-2 papers per year). The number of the three task categories (Fig. 5) also illustrated a sluggish growth over time, with a nearly linear fitting trend. The observed data for 2020 in all of the categories above are lower than predicted, which indicates that COVID-19 has a significant impact on global scientific research. The distribution of the reviewed works across the different categories is presented in Fig. 2.

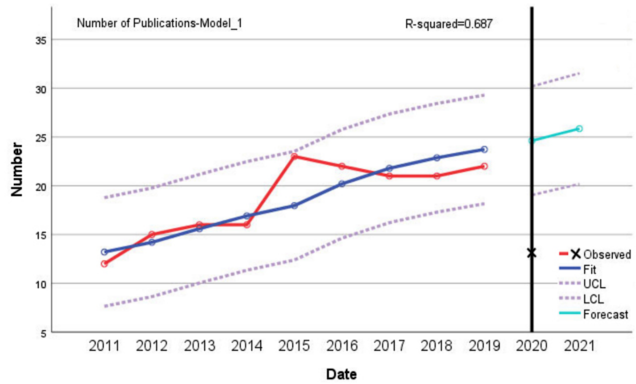

Fig. 3. Number of total publications and forecasts over time.

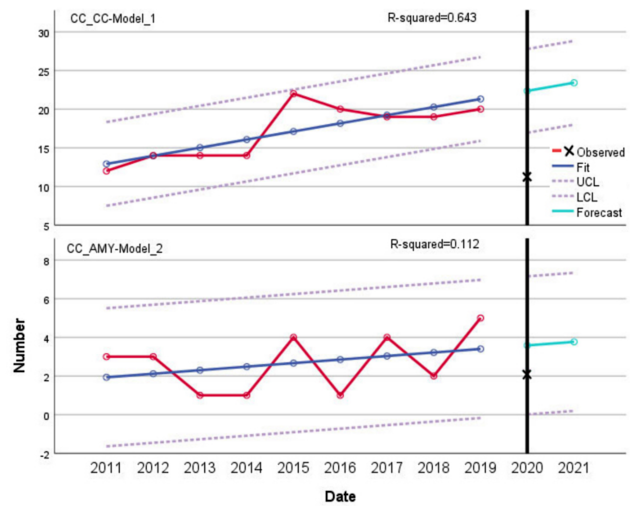

Fig. 4. Number of publications and forecasts on effective connectivity categories over time.

A. Effective Connectivity

1) FC-FC: The interactions between FC and FC is involved in numbers of literature, with 78 publications [4], [3], [8]–[83]. Overall, these publications cover all of the task types included in our taxonomy (see the last column of Fig. 2), of which the more relevant are upper limb movement, sensory tasks, and disease diagnosis.

2) FC-PC: This is the most frequent effective connectivity category in the literatures, with 80 publications [4], [8]–[16], [17]–[23], [26]–[28], [30], [31], [33], [35]–[42], [45], [54]–[56], [61], [66], [70]–[73], [75], [76], [78], [80]–[82], [84]–[104], [106]–[117] and 11 different task types covered. Like FC-FC, upper limb movement, sensory tasks, and disease diagnosis being also the most used.

3) FC-OC: We found 27 papers [3], [23], [35], [47], [57]–[59], [65], [69], [77], [86], [94], [96], [97], [99], [100], [118]–[128] involved in this connectivity category, spanning eight different task types, of which disease diagnosis had the highest prevalence.

4) FC-TC: We found 30 publications [3], [29], [33], [36], [44], [51], [56], [57], [63], [67], [111], [115], [120], [121], [124], [129]–[137] on this connectivity category. Eight task types were proposed for its analysis, the most frequent being sensory tasks, speech tasks, and disease diagnosis.

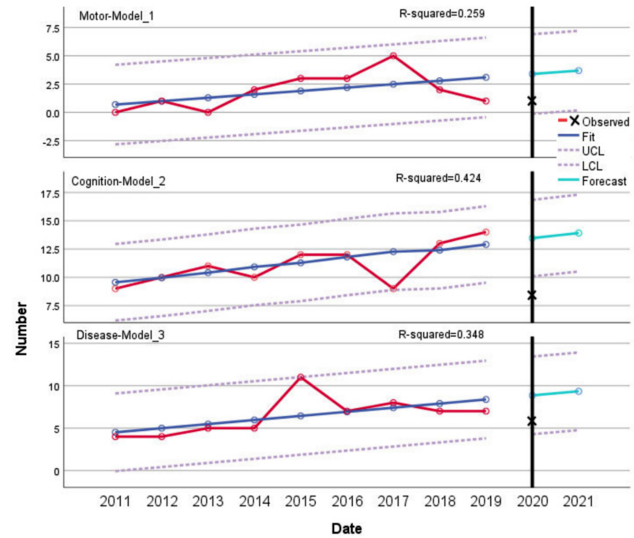

Fig. 5. Number of publications and forecasts on task types over time.

5) PC-PC: With 55 publication, [4], [10], [11], [13]–[16], [17]–[23], [27], [28], [31], [35]–[39], [41], [42], [54], [61], [67], [70]–[73], [76], [81], [87]–[90], [101]–[107], [109], [112]–[114], [117], [138]–[142], [144], [145], this is the third most considered connectivity category in this review. Ten different task types were presented and the most relevant were upper limb movement, sensory tasks, and disease diagnosis.

6) PC-OC: The interactions between PC and OC is the fifth most covered connectivity category, with 29 publications, [23], [27], [35], [39], [45], [71], [87]–[89], [92]–[94], [96], [98], [99], [115], [120], [124], [141], [142], [146]–[154]. The most frequent task types were sensory tasks.

7) PC-TC: Twenty papers, [26], [36], [56], [63], [67], [73], [76], [98], [100], [106], [108], [111], [120], [124], [129], [133], [141], [143], [144], [154], covered this connectivity category, with 7 different task types, the most relevant being disease diagnosis.

8) OC-OC: We found 24 publications [27], [35], [39], [45], [58], [59], [77], [87], [100], [118], [121], [122], [142], [144], [149], [150], [153], [155]–[161] that studied the interactions between OC and OC. Seven task types were presented for this analysis and the most relevant was sensory tasks.

9) OC-TC: We found 23 papers [26], [44], [57], [87]–[89], [100], [115], [121], [124], [126], [141], [144], [149], [151], [154], [155], [157], [161]–[165] covering this connectivity category, spanning seven different task types, of which sensory tasks had the highest prevalence.

10) TC-TC: There are 24 publications, [3], [29], [36], [51], [67], [73], [74], [76], [88], [89], [100], [105], [121], [132], [134], [136], [137], [155], [161], [162], [164]–[167], studied the interactions between TC and TC. As in the previous case, seven task types were presented and the most relevant were sensory tasks, speech tasks, and disease diagnosis.

11) FC-INS: Nine papers, [30], [34], [62], [71], [79], [110], [128], [131], [145], involved in this connectivity category, with a heterogeneous set of task types (please refer to Fig. 2 for more details).

12) FC-HPC: Eight papers, [60], [64], [79], [97], [115], [168]–[170], focused on this connectivity category. Five task types were proposed for its study: memory tasks, emotional tasks, decision-making, disease diagnosis, and drug effect.

13) PC-INS: We found four publications [30], [71], [131], [145], that considered this scenario, with three cognitive tasks proposed: sensory tasks, emotional tasks, and disease diagnosis.

14) PC-HPC: Only one paper [115], covered this category, with one task type: disease diagnosis.

15) OC-INS: We found two papers [71], [160] covering this connectivity category. The analysis of certain cognitive tasks and disease diagnosis were the task types considered.

16) OC-HPC: Only one publication [171] was found in this category, focusing on the analysis of disease diagnosis.

17) TC-HPC: Only one paper [115] was found on this category. One task type was employed for this analysis: disease diagnosis.

18) INS-HPC: We only found one paper [79] covering this connectivity category, which focused primarily on drug effects.

19) FC-AMY: There are twenty papers [43], [46]–[48], [69], [83], [97], [110], [119], [123], [143], [168], [169], [172]–[177], [179] involved in the study of interactions between FC and AMY. Five task types were presented and the most relevant were emotional tasks and disease diagnosis.

20) PC-AMY: Only two publication, [174], [175], covered this connectivity category. Disease diagnosis was the task type considered.

21) OC-AMY: Six papers, [26], [69], [119], [146], [174], [179], covered this connectivity category, with four different task types: sensory tasks, emotional tasks, disease diagnosis, and drug effect.

22) TC-AMY: We found three publications [142], [149], [180] that studied the interactions between TC and AMY. Two cognitive tasks were presented: sensory tasks, and emotional tasks.

23) INS-AMY: Only one paper [110] were found in this connectivity category, focusing on the analysis of disease diagnosis.

24) HPC-AMY: We found three publications [168], [169], [181], that considered this scenario, with two cognitive tasks proposed: memory tasks, and emotional tasks.

25) FC-BG: Three publications [152], [178], [182] were found on this category. Two task types were employed for this analysis: decision-making and drug effect.

26) PC-BG: Only one paper [152] covered this category. One task type was proposed: decision-making.

27) INS-BG: Only one paper [183] covered this connectivity category. Emotional tasks were the task type considered.

28) HPC-BG: Only one publication [79], covered this category, with one task type: drug effect.

29) FC-Thal: We found twelve publications [34], [63], [64], [72], [78], [82], [83], [125], [152], [178], [184], [185] that studied the interactions between FC and Thal. Five different task types were presented: sensory tasks, decision-making, other cognitive tasks, disease diagnosis, and drug effect.

30) PC-Thal: Five papers, [72], [82], [145], [154], [184], covered this category, with two task type: disease diagnosis and drug effect.

31) OC-Thal: Only one paper, [152], covered this category, with one task type: decision-making.

32) TC-Thal: We found two publications, [63], [154], that considered this scenario, with two disease-related tasks proposed: disease diagnosis and drug effect.

33) INS-Thal: We found three papers [34], [183], [186] covering this connectivity category. Two task type was proposed: sensory tasks and emotional tasks.

34) AMY-Thal: Only one paper [83] covering this category, which focused primarily on drug effect.

35) BG-Thal: Three papers [152], [178], [183] were studied the interactions between BG and Thal, with two different task types: emotional tasks, decision-making, and drug effect.

B. Task Type

1) Motor Tasks of Upper Limbs: This type refers to the movement of hands, especially the fingers. Motor tasks of upper limbs were used to measure the effective connectivity of different brain regions in 16 publications. These covered the following specific tasks: finger-pinching execution and imagery, finger-tapping execution and imagery, finger extension/flexion execution, out-and-back finger movement, squeeze and release a ball, hand force-tracking task, wrist extension/flexion execution, and fist closures task.

2) Motor Tasks of Lower Limbs: We found only one paper mentioning this category. The task required the subjects to perform continuous passive motion (CPM) of the ankle.

3) Motor Tasks of All Four Limbs: This task type has been also involved in only one paper, it required the subjects to perform wrist and ankle flexion movements.

4) Stimulation of Different Sensory Channels: This type includes eight different sensory tasks such as visual, auditory, tactile, vibrotactile, thermal, gustatory and electrical stimulation as well as cold-stimulating pain. It is the second most commonly used task type in this review (TABLE I), with 43 appearances in papers, spanning 16 different effective connectivity categories.

5) Memory Tasks: The memory tasks were proposed by 13 papers. Nine specific tasks were identified: immediate memory task, delayed memory task, the n-back task with letters, numbers, and pictures, multi-source interference task, Think/No-Think task, Sternberg item recognition task, and autobiographical memories (AM) retrieval task.

6) Emotional Tasks: Emotional tasks are mainly triggered by visual or auditory stimuli. Nine task types were proposed in 16 publications and 18 effective connectivity categories were determined. The nine tasks included emotional face discrimination, object discrimination, emotional face-matching, emotional film clips feedback task, emotional sounds discrimination, neurofeedback task with social images, picture encoding task, free recall memory test, and empathy & Theory of Mind (EmpaToM) task.

7) Speech Tasks: This kind of task was found in 18 publications, all of them focusing on the interactions between CC and CC. Thirteen tasks were involved: speech discrimination, semantic matching task, picture naming task, gesture-speech integration, make predictions about the onset of a speech sound, semantic-based therapy task, Stroop test, semantic feedback task, tone judgment task, dialogues stimuli, rhyming task, phoneme detection task, semantic categorization task.

8) Decision-Making Tasks: This type of task is also based on visual stimuli. It was used in almost all effective connectivity categories, except for the interactions between AMY and Thal. The specific tasks used were target recognition in different visual fields, numbers detection and repetition, incentive-compatible free-choice tasks, as well as event and object generation.

9) Other Tasks Related to Cognition: Eleven publications were found covering this aspect. It refers to all other cognitive tasks that do not belong to the mentioned five types. Most studies focused on the default mode network in the resting-state. Reaction time task, monetary incentive delay task, familiarity judgement of faces, focusing on self condition or other conditions while watching a set of video-vignettes, and button-press with/without the restriction of movement lateralization or/and timing, were the other five tasks found in this category.

10) The Tasks Related to Disease Diagnosis: This type is the most considered in the literature, with 48 appearances in papers, spanning 24 different effective connectivity categories (TABLE I). We found 24 different specific tasks, the most frequent being resting-state fMRI, n-back tasks, emotional face discrimination, object discrimination, and image matching of different targets.

11) The Tasks Related to Drug Effect: Eight different tasks have been proposed in 16 publications, all of them focusing on the changes in effective connectivity resulting from different drugs. The most frequent were resting-state fMRI after drug intervention and repetitive finger movements after drug intervention.

C. Data Source

As shown in Fig. 6, further analysis of the research data sources indicated that the number of studies based on fMRI accounted for the vast majority of the total, but it has stopped increasing after 2015 and leveled off gradually; the number of studies on EEG has generally increased slowly over time, and predictive model shows that research on EEG should increase further excluding the factor of COVID-19. DCM has only recently been applied to adult fNIRS, there are not many related studies, and its number showed a nearly linear growth.

IV. Discussion

We observed an increasing relevance of identification of interacting networks in the brain using DCM. This fitting trend, visible in the nearly linear growth in the numbers of papers (Fig. 3) is, however, only in part accompanied by an increase in the range of effective connectivity and related tasks that are researched, which show a more moderate increment. This, together with our taxonomic analysis summarized in

TABLE I
Overview of the Tasks Found on the Reviewed Works Engaged in the Three Main Types

Task	**Motor tasks**	Upper limb	Finger-pinching execution and imagery, finger-tapping execution and imagery, finger extension/flexion execution, out-and-back finger movement, squeeze and release a ball, hand force-tracking task, wrist extension/flexion execution, fist closures task.
		Lower limb	continuous passive movement (CPM) of the ankle
		All four limbs	Wrist and ankle flexion movements
	Cognitive tasks	Sense	Visual stimulation, auditory stimulation, tactile stimulation, vibrotactile stimulation, electrical stimulation, cold-stimulating pain, thermal stimuli, gustatory stimuli.
		Memory	Immediate memory task, delayed memory task, n-back task with letters, n-back task with numbers, n-back task with pictures, multi-source interference task, Think/No-Think task, Sternberg item recognition task, AM retrieval task.
		Emotion	Emotional face discrimination, object discrimination, emotional face-matching, emotional film clips feedback task, emotional sounds discrimination, neurofeedback task with social images, picture encoding task, free recall memory test, EmpaToM task.
		Speech	Speech discrimination, semantic matching task, picture naming task, gesture-speech integration, make predictions about the onset of a speech sound, semantic-based therapy task, Stroop test, semantic feedback task, tone judgment task, dialogues stimuli, rhyming task, phoneme detection task, semantic categorization task.
		Decision-making	Target recognition in different visual fields, numbers detection and repetition, incentive-compatible free-choice task, event and object generation.
		Others	Resting-state fMRI, focusing on self condition or other condition while watching a set of video-vignettes, button-press with/without the restriction of movement lateralization or/and timing, reaction time task, monetary incentive delay task, familiarity judgement of faces,
	Disease-related tasks	Disease diagnosis	Resting-state fMRI, detection on a rapid successive visual presentation, thinking of an appropriate word to complete an incomplete sentence and press the button simultaneously, letter n-back task, continuous picture viewing, emotional face discrimination, object discrimination, Stroop task, verbal n-back task, gesture-speech integration, target recognition in different visual fields, resting-state EEG, EEG recording during different paradigms, image matching of different targets, object-location associative learning task, event-related fMRI, numeric n-back task, emotional n-back task, standard neuropsychological test, auditory paced finger sequence tapping task, delayed-response working memory task, salience integration task, finger-tapping task, reward learning task.
		Drug effect	fMRI after drug intervention, auditory stimuli caused by familiar names during the loss of consciousness induced by propofol, emotional face discrimination after drug intervention, picture n-back task, Cocaine-word Stroop task, repetitive finger movements after drug intervention, EEG recording during different paradigms, Go/NoGo response inhibition task.

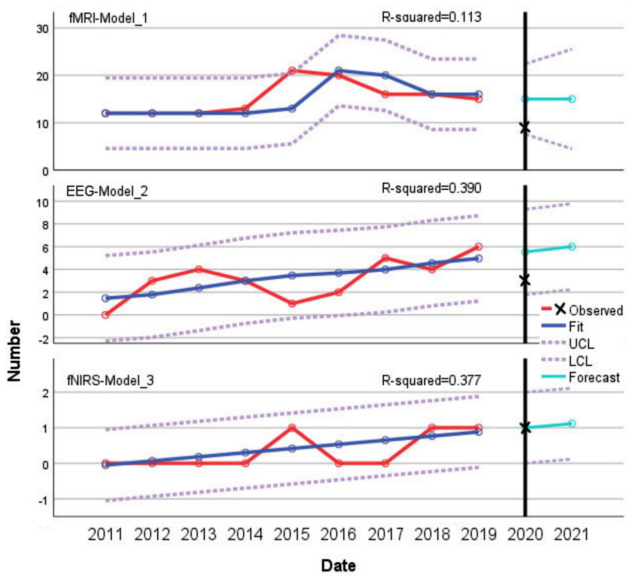

Fig. 6. Number of publications and forecasts on related data sources over time.

Fig. 2, demonstrates that the current research methods for coupling between brain regions are still restricted to a small portion of the applicable task types and effective connectivity categories. In the following sub-sections, we will consider in more detail the possible causes of this situation.

A. Effective Connectivity

The number of papers focusing on the interactions between CC and CC prevails by one or two orders of magnitude over any other effective connectivity categories considered in our taxonomy, of which FC-FC, FC-PC, and PC-PC are the most numerous in the CC-CC category. FC is the largest lobe of the brain and makes up about a third of the surface area of each hemisphere, it is devoted to different actions, such as skeletal movement, ocular movement, speech control, and the expression of emotions, etc., [187]. The PC plays important role in integrating sensory information from various parts of the body, knowledge of numbers and their relations, and in the manipulation of objects. It also includes many other functions such as processing information relating to the sense of touch [187]. Therefore, all of the tasks mentioned in Fig. 2 involved the connection between the FC and the PC. In our opinion, however, the dominance of more effective connectivity between certain brain regions does not imply that the effective network between other brain regions is less relevant. A simple task in daily activities often requires multiple brain regions to cooperate to complete. The current analysis shows that in the CC-CC category, there are too few effective connectivity analyses related to INS and HPC, with only 28 publications (6.7% of the total), especially those related to PC-HPC, OC-INS, OC-HPC, TC-HPC, and INS-HPC. This may be explained by the fact that the connection mechanism of these brain regions is not well understood and is still under exploration. In particular, the paper accidentally discovered that INS and HPC are connected during the study of the anterior cingulate cortex (ACC) to HPC effective connectivity in response to the drug [79].

The BG is of major importance for normal brain function and behavior. They are associated with a variety of functions such as control of voluntary motor movements, eye movements and emotion, etc. [188]. Another brain region involved in motor tasks is the Thal. The Thal has multiple functions, generally believed to act as a relay station, or hub, relaying information between different subcortical areas and the CC [187]. However, none of the papers studied the interaction between BG or Thal and other brain regions in motor tasks. It is most likely although the functions of BG and Thal have been recognized, the mechanism of their connection with other brain regions is still poorly understood. Moreover, BG and Thal are close to the center of the brain. Generally, the electrophysiological and hemodynamic data of the deep brain cannot be obtained by using EEG and fNIRS, and can only be measured with the help of fMRI in most cases. Therefore, the limitation of research methods may also lead to this situation.

B. Task Type

In the category of motor tasks, upper limb tasks are more than the other two types. Their experimental design is usually relatively simple, and it is easier to implement the activation of the corresponding CC in related studies. Despite these practical advantages, we consider them insufficient to reflect the activation of the CC by all modes of motion. The motor tasks that have been particularly disregarded in the literature are the movement or motor-imagery of the lower limbs (one paper), all four limbs (one paper), and other parts of the body (no paper). We consider that these aspects are worthy of further research, since they often present in many daily activities, rehabilitation treatments, and other realistic scenarios, and with the further intensification of demographic aging, the elderly's demands for rehabilitation, especially exercise training, are gradually increasing. The lack of research on non-upper limb motor tasks in the literature may be related to the method of the research data acquisition. In general, fMRI and EEG require subjects to keep their bodies stationary during the experiment. Although fNIRS is not sensitive to subjects' head movements, its data has not been applied to DCM for a long time, and there are still few related studies at present.

The category of cognitive tasks is extremely popular in the study on identification of interacting networks in the brain by means of DCM. This is probably due to the fact that fMRI and EEG are traditional imaging technologies in the field of cognitive neuroscience. After years of development, both of them have established experimental tasks and relatively mature experimental paradigms. Therefore, cognitive tasks accounted for the vast majority in this review. In addition, sensory tasks are the largest type in the category of cognitive tasks. This may be explained by the fact that the sensory system is an important way for people to interpret information from the physical world and create perceptions of the world around them. Another interpretation is that visual, auditory, and other sensory tasks in most cases only need to perform simple stimulation on the corresponding sensory channels.

It is relatively easier to implement in experimental design than emotion regulation, speech activities, and other cognitive tasks. There are not many studies related to memory tasks, however, it is worth noting that all memory tasks are directly related to working memory, and it seems that researchers are very interested in how working memory load modulates brain connectivity through different n-back tasks. Emotion and speech are two other popular types of cognitive tasks. The difference is that the emotional tasks are relatively simple and mainly focus on analyzing the effective connectivity between different brain regions through emotional visual stimuli. The specific types of speech tasks are more diverse, involving language, semantics and gesture-speech integration, etc. Nevertheless, we believe that they should receive more attention in the future, especially the former, because emotional tasks involve 20 effective connectivity types, but most of them are supported by only one publication, their effectiveness needs to be further explored. The same applies to decision-making tasks. They involve multiple brain connectivity, but are still poorly considered in the literature and should therefore receive more attention in the future. The default mode network (DMN) is part of the brain structure which shows higher neural activity when one is at rest, it has always been a research hotspot in the field of neuroscience. Therefore, resting-state fMRI is the most common task type among other cognitive tasks. Some of the individualized tasks associated with different studies, such as focusing on self condition or other conditions while watching a set of video-vignettes and button-press with/without the restriction of movement lateralization or/and timing, are also classified as the type of other cognitive tasks.

In the category of disease-related tasks, disease diagnosis is a very important and popular type. In our opinion, these tasks are closely related to the cognitive tasks mentioned earlier, because the vast majority of the diseases in these researches are psychiatric disorders which characterize by a multitude of symptoms affecting a variety of cognitive domains. Because of this, some of the tasks in this type are the same as the category of cognitive tasks, while some are new. As a result, the number of tasks related to disease diagnosis is the largest of all categories. The diseases in the literature mainly involved schizophrenia and depression, with 21 publications. Others such as posttraumatic stress disorder, social anxiety, amyotrophic lateral sclerosis, autism, epilepsy, irritable bowel syndrome, and smoking addiction are supported by only less than two research each. Understanding the neural basis underlying various psychiatric disorders is essential for the diagnosis and treatment of such disorders. Therefore, in our opinion, research directions related to this task type are particularly promising. The same applies to the type of drug effect. The changes in effective connectivity resulting from drug-induced functional and neurological abnormalities vary widely. At present, however, the effects of most drugs are rarely studied by researchers, they still have a long way to go.

C. Data Source

The fMRI has always been the most commonly used data source for researchers to use DCM to infer effective connectivity. Although research based on EEG and fNIRS data has gradually increased in recent years, these two techniques are generally unable to detect brain activity in deep subcortical nuclei, which has led to the largest number of fMRI-based studies in this review. However, fMRI and EEG are more sensitive to the subjects' head movements, so they cannot accurately record the brain's responses when the infants are awake. On the contrary, the fNIRS devices can realize data collection in various occasions and locations, and have a high tolerance to the movement of the subjects. Therefore, in recent years, research on brain connectivity based on fNIRS data are gradually increasing.

D. Limitations

The brain connectivity analyzed by DCM is directional, but due to the numerous brain regions involved, the number of directed networks is too large. Therefore, this review did not focus on the directed network between the concerned brain regions, which is nonetheless an important aspect that should be addressed in future analysis and research.

Generally, emotional and cognitive tasks should be two types of tasks, rather than subordination, but in almost all literature, emotional tasks are implemented through emotional sensory stimuli. Therefore, this review classifies emotional tasks as a sub-type of cognitive tasks without further distinction.

V. Conclusion

This review revealed an increase in the number of publications focused on analyzing brain connectivity using the DCM method excluding the factor of COVID-19, which demonstrates that, in general, the scientific community has a growing interest in the identification of interacting networks in the brain. We found that there was large heterogeneity in the distribution of the effective connectivity category. Most research focused on the networks between different cortical regions except INS and HPC. This highlights that the connectivity between the various regions of the CC is still an area of great concern to the scientific community. Research on the networks between other deep subcortical nuclei (such as AMP, BG, and Thal) or between them and CC are receiving increasing attention, but far from the same scale. In particular, some effective connectivity categories have only one related paper in the past 10 years, which requires further research to support. Over the years, some task types have mature experimental paradigms, such as emotional stimuli discrimination, n-back tasks, and resting-state fMRI. There are also task types that are receiving increasing attention but still cannot be considered to have reached the same level of maturity. Motor tasks of lower and all four limbs, for example, have been greatly overlooked in the literature, together with other types which including decision-making and other cognitive tasks. We consider that performing different tasks to discover the corresponding brain network connections is very important for understanding the brain's information processing. Especially in the field of rehabilitation, robots are increasingly involved in people's rehabilitation process, but the scientific community has mixed opinions on the effect of robot-assisted rehabilitation [189].

Modern rehabilitation medicine is based on the theory of neuroplasticity [190], so it is particularly critical to study the brain network in the process of robot-assisted rehabilitation. This requires the coordination of multiple tasks, but so far, there are still too few studies related to some tasks mentioned above. Nevertheless, different data sources play different roles in different task types. For example, the fNIRS devices are better at hyperscanning and motor task analysis. We can take advantage of these features to increase further research and exploration.

The results of this review can give people a clear understanding of what aspects have been overlooked in the study on the identification of interacting networks in the brain with DCM in the past decade. We hope that the results will not only answer the three questions raised in Section I, but also point towards relevant future research directions.

Disclosure Statement

The authors report no conflicts of interest. They alone are responsible for the content and writing of this article.

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