The Role of the Neural Mirroring System in Human Infant Imitation

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Humans imitate the actions of others as means of social learning. This behavior is especially prevalent in infants before they learn how to communicate through verbal language. For decades, researchers have explored the neural basis of infant imitation, increasingly attributing it to the role of mirror neurons. Therefore, the primary aim of this paper is to explore the specific contribution of the neural mirroring system to infant imitation abilities. Infant EEG studies indicate that mirror neurons play a role in imitation and suggest that a neural mirroring system is activated when infants are engaged in social contexts such as when they are learning to imitate goal-directed actions or form social bonds. To understand the neural processes involved in infant imitation, researchers utilize various experimental paradigms. These include tasks where infants observe actions performed by others, tasks where they perform actions themselves, and tasks involving interactive social exchanges. When EEG has been used in combination with these experiments, researchers have consistently found shared neural activity patterns in infants. Some of these findings include the identification of mu desynchronization over central electrode sites during action execution and prior to the onset of observed actions. Although EEG has limitations as a tool for studying infant cognition, the compelling findings can be used as the basis for potential clinical and educational applications regarding infants.

Introduction

As an infant grows, one of their first moments of joy is when they smile back at their parents. Another special moment is when they finally say the word that their parents have been repeating to them since they were born. And later on in life, they will begin to behave just like those around them. Imitation is a crucial social behavior that shapes one's skill development by allowing them to learn from the environment and those around them.

In the simplest terms, imitation means to voluntarily copy or match the behavior of others [1]. This is especially seen in human infants, as they are constantly imitating a wide variety of behaviors, including motor, vocal and object-related actions. The infant then learns to use the actions of others as a foundation for their own actions. The development of this social behavior occurs for many important reasons. Specifically, imitation allows people to improve their socialization skills [2], and acquire skilled motor actions at a faster rate by reducing the trial-and-error attempts that happen when learning in isolation takes place [3].

In Piaget's Theory of Imitative Development [4,5], he suggests that imitation is involved with cognitive development, with infants progressing in the level and difficulty of imitative behaviors over the first several years of life. While there is disagreement on at what age infants are able to begin imitating [1,6], there is an agreed consensus that imitative behavior is seen in older infants (nine to eighteen months of age). What could explain how infants are capable of imitation at this early stage? It was only a few decades ago when researchers discovered a neural mechanism that appeared to elucidate human imitative abilities: the mirror neuron system [1].

Mirror neurons, originally discovered by Di Pellegrino and his team of researchers in 1992, are believed to be some of the primary neural mechanisms that underlie infant imitation. Mirror neurons are a class of neurons that fire both during the observation of others performing an action as well as when those actions are executed by the observer [7]. In this way, they aid in understanding the actions of others and in developing social bonds. Investigating mirror neurons in infants as they try to imitate others' actions can provide a deeper understanding of how humans learn from one another and grow social connections.

Before exploring studies presenting evidence for the role of mirror neurons in imitation, it is important to first understand the background of mirror neurons and what methods are commonly used to study them.

The discovery of mirror neurons

"Mirror neurons" are a class of cells that activate, or in other terms, repeat a representation of a motor action, when a person performs that action at the same time as a person they are observing. Mirror neurons were initially found in macaques (monkeys) when they performed a certain action and observed the same being demonstrated by another animal. In both action observation and execution, the same group of neurons fired in area F5 of the ventral premotor cortex [8]. Since their discovery, a large body of evidence now suggests that mirror neurons also exist in the human brain [9,10]. One theory for why mirror neurons exist

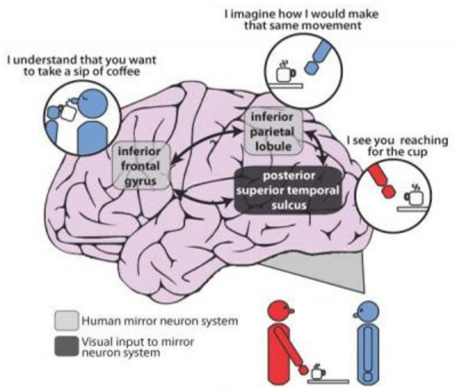

Fig. 1 Activation of the neural mirroring system[20]

is that they may help the observer understand the ”meaning” of the action being shown by the performing individual[11]. For example, if an observer notices a person throwing a basketball into a hoop, then a representation of this same act will be played in their brain so that they can understand how the intent is to get the ball to fall through the hoop. In addition, it has been argued that aside from helping with understanding actions, the mirror neuron system also helps predict the occurrence of an action[11].

Evidence to support the theory that mirror neurons serve an important neural functioning in imitation stems from functional magnetic resonance imaging (fMRI) studies in humans showing that brain areas responsible for imitative behavior coincide with the same regions in macaques where mirror neurons were found[12]. Moreover, adult studies that used fMRI, magnetoencephalography (MEG), electroencephalography (EEG), and transcranial magnetic stimulation (TMS) have revealed that action observation and execution are facilitated by similar neural circuits[13].

While some researchers believe that a “mirror neuron system” is fundamental to imitation,[12,14,15], others argue that there are not enough empirical findings to support this[16–18]. In order to resolve the controversy over the characterization of the mirror neuron system, the term ”neural mirroring system” can be used instead to point out that although its exact properties are still being investigated, there is an evident neural circuitry that supports observation–execution coordination[13,19]. In this paper, the individual cells comprising this neural mirroring system will still be referred to as “mirror neurons,” but the broad term to describe the brain networks involving them will be referred to as a “neural mirroring system.”

The sensorimotor mu rhythm as a measure of mirror neuron activity

To study imitation, researchers commonly place subjects in conditions where they observe and execute actions being performed by an experimenter. Throughout this process, the researchers will use EEG to observe the subjects’ neural activity (e.g.[21**?**–23] - in particular by measuring desynchronization of the sensorimotor mu rhythm.

The mu rhythm is an EEG oscillation most commonly found over central scalp regions that approximately ranges between 8-13 Hz in adults and 6-9 Hz in infants and young children[24]. It is produced most clearly during resting state and becomes desynchronized, or reduced in power, immediately before or during motor events[25,26]. Some researchers believe that this rhythm is an indicator of the activation of a neural mirroring system in humans because it is desynchronized when individuals observe or imitate an action being formed by another individual[27,28]. The mu rhythm is also highly correlated to the activation of the motor cortex when planning and performing actions[26,29]. Therefore, researchers have suggested that the mu rhythm is associated with mirror neuron activity when infants are imitating[2]. However, because the evidence is correlational, mu desynchronization may also be associated with other cognitive processes, such as attention, which is further evaluated in “(ii) Attention as a cognitive property of the neural mirroring system” in the Discussion section.

What role does the neural mirroring system play in facilitating human infant imitation?

This paper aims to answer the research question, “What role does the neural mirroring system play in facilitating human infant imitation?” This question will be explored in regards to how infants 1) imitate others’ motor actions and 2) form social bonds through imitation. Therefore, this paper will first examine examples of EEG studies that show the neural activity found in infants when they were imitating motor and social behavior, followed by an exploration of patterns found by other researchers regarding this neural activity, and finally, it will address the limitations and improvements to this area of research. The main area of focus in this paper is the EEG evidence that suggests the existence of an underlying neural mirroring system in infants performing imitative activities. Understanding the role of the neural mirroring system in infant imitation provides insights into early development, which can help researchers apply this knowledge to clinical and educational research. This is further discussed under the Limitations and Improvements section.

Evidence supporting a neural mirroring system in human infant imitation

How the neural mirroring system contributes to imitating motor behavior

One of the primary goals of imitation is to understand motor actions being performed by others. This section will outline several studies that suggest that mirror neurons are activated when infants are imitating motor movements. The following studies designed procedures in which infants were taught to imitate a certain goal-directed action, thus requiring action understanding to take place. Importantly, these studies suggest the activation of a consistent neural mirroring system during these tasks.

One question regarding mirror neurons is when and where within the brain they are active during imitative behaviors. In 2011, a group of researchers,[21], recorded EEG in thirty-eight 14-month-old infants as they watched and then performed a goal-directed act, a button press, being demonstrated by an experimenter. The researchers compared the reactivity of the infant EEG rhythm during the action observation and execution conditions to a baseline condition, in which they were exposed to an abstract visual pattern. The researchers found significant mu desynchronization at central electrode sites, which corresponded to the sensorimotor cortex, when the infants were executing the actions. A similar pattern was found during observation of the act. However, the activity during action observation extended to frontal and parietal scalp regions. These findings coincide with EEG studies done on adults[30–33]. Overall, the central region was the single scalp region that showed a common neural pattern during both action execution and observation, which is consistent with studies done on the adult mu rhythm[27]. This study suggested that mirror neuron activity in infants was present within the sensorimotor cortex.

Debnath et al. (2018) also investigated which regions were active during imitative activity. They investigated mu frequency as thirty-seven nine-month-old infants observed experimenters grasping a toy and then grabbed the toy themselves. They found mu desynchronization during action observation and execution as well as prior to the onset of the observed action. Unlike Marshall et al., (2011), the researchers found that in both experimental conditions, mu desynchronization took place over frontal, central, parietal and occipital electrode sites, which also coincides with previous research[21,34,35]. In addition, the researchers performed a connectivity analysis and found that during action observation, the central and occipital regions were more functionally connected compared to other brain areas. This study suggested that mirror neuron activity in infants was present within the motor and visual cortices.

Southgate et al. (2009) conducted a similar study in order to better identify when mirror neurons are active during motor behavior in infants. They used EEG to detect changes in the mu rhythm when fifteen nine-month-old infants observed an experimenter reaching for a small graspable toy and executed the same goal-directed action. Similarly to Marshall et al. (2011), the researchers found mu desynchronization in both action observation and execution conditions in the sensorimotor cortex. Interestingly, mu desynchronization was also present as infants began to anticipate the occurrence of the observed action, similarly to Debnath et al. (2018). This predictive element was similarly found in adult EEG studies[36]. These results indicate that infants, like adults, demonstrate overlapping neural activity during the observation and execution of actions, and that this activation is driven by infants' understanding of an anticipating action as opposed to just visual input.

In slight difference to the aforementioned studies, Warreyen et al. (2012) examined mu desynchronization as thirty-five 18-to-30-month-old infants observed and executed a goal-directed action, in addition to while they performed a non-goal-directed action. The goal-directed action involved a hand moving a toy in a specific sequence inside a box. The researchers regarded these actions as 'goal-directed' because they always had a clear end position within the box. Meanwhile, the non-goal-directed action involved only a hand that moved in the same manner as in the action observation condition. Similarly to Marshall & Meltzoff (2011), the researchers found the strongest mu desynchronization over central electrode sites during execution, while there was a widespread distribution including frontal and parietal regions during observation. However, the infants displayed significantly stronger mu desynchronization during the observation of the non-goal-directed action compared to goal-directed. Previous research has found that similarly to adults but on the contrary to younger infants, 18-to-30 month olds exhibit such motor activity when viewing unpredictable hand movements[22,37]. This finding is interesting because in contrast to the belief that mu suppression primarily reflects motor goals[37,38], it may also account for the observation of unpredictable physical movements. The study suggests that mirror neuron activity in infants extends across the frontal and parietal lobes.

The aforementioned infant EEG studies have provided evidence suggesting a neural mirroring system that extends to regions that are associated with visual activation, such as occipital sites (e.g.[13,39]) during action observation, as well as regions that are associated with motor activation, such as central sites[21] during both action observation and execution. The compelling finding that motor activation occurs when an unpredictable hand movement is observed[39] was accounted for by the researchers' explanation that the motor cortex may respond similarly or even more strongly to observing the movement of a body part, such as a hand in the present study. In addition, the finding that motor activation occurs prior to the onset of an action being performed[22,23] suggests that the ability of the neural mirroring system to predict actions may be because its mental representation is being stored in motor areas. However, even with observing consistent activity that suggests the existence of a common neural mirroring system in infants, researchers have not yet identified an exact neural mechanism that takes place during action observation because imitative contexts vary from individual to individual. Future advancements of technology that can closely trace and examine the neural circuitry during such imitative contexts, beyond just detecting "activation" in certain brain regions, can deeply expand the current knowledge of action understanding and its role in the infant imitation of motor behavior.

How the neural mirroring system contributes to imitating social behavior

Another primary goal of imitation is to build stronger social bonds. The following studies placed infants in dyadic imitative contexts (an interaction between two people), and found a consistent neural mirroring system that activated when an infant's behavior was being matched by the interacting adult.

In 2012, a group of researchers[40] recorded EEG in 44 14-month-old infants as their actions were imitated by an experimenter, as opposed to the infants imitating the actions of the experimenter as in the previous studies discussed. During the action execution condition, the infant pressed a button or grasped a toy, and then during the action observation condition, the infant watched the experimenter imitate them or perform a different act. The researchers found mu desynchronization in both the action execution condition as well as observation conditions in which the infant's preceding act was matched by the experimenter, but not when the experimenter was performing a random action. In addition, they also found this desynchronization prior to the onset of the experimenter performing the button press, which has also been seen in other studies[22,23]. While previous studies[13,22] have implicated the sensorimotor cortex facilitates the neural mirroring system, this study suggests that infant mirror neuron activity also occurs within the somatosensory cortex.

Similarly, Reid et al. (2011) measured EEG in 10 14-month-old infants across baseline, non-interactive, and dyadic interaction conditions. In the non-interactive condition, the infant was exposed to an adult performing actions that were beyond the motor capabilities of the infant, as well as without communicative body language. Meanwhile, in the dyadic interaction, the infant and experimenter were engaged in a direct face-to face imitative game. The researchers found significant mu desynchronization when the infants were involved in dyadic interactions compared to the other two conditions. This result aligns with other adult and children studies[41–43]. Moreover, there were no differences in rhythmic oscillations between the non-interactive and baseline conditions. Similarly to Debnath et al. (2018), the current study suggests that mirror neuron activity was present within the motor cortices.

Overall, Saby et al. (2012) and Reid et al. (2011) found that a similar mu desynchronization takes place when an infant's behavior is being matched by others. This pattern, alongside the finding that mu desynchronization also takes place when infants anticipate an action, provides evidence that suggests that a neural mirroring system is prevalent during the imitation of social behaviors. Saby et al. (2012) showed that mu desynchronization was more prominent when an infant's prior act was imitated by an experimenter, while Reid et al. (2011) found the most distinct mu desynchronization when the infant's actions were being imitated in more continuous, social interactions. It can be argued that the same neural mirroring system that is present in such social bonding contexts also underlies action understanding. This is interesting because it suggests that the neural mirroring system in infants is flexible in terms of the spectrum of imitative situations that it responds to, although this theory still requires more empirical support.

Discussion

In summary, consistent findings of mu desynchronization during the imitation of motor or social behaviors suggest that these processes are facilitated by a neural mirroring system. While the exact circuitry of this neural mirroring system within the visual and motor areas in the infant brain is still unknown, there are other interesting patterns found across the infant studies mentioned in this paper that may provide further insight into this system's distinct functions and properties during imitative situations.

Patterns of the neural mirroring system

1. **Mu desynchronization is not consistently found in the same brain regions across different imitative situations** While mu desynchronization has been consistently detected across central, parietal, and occipital sites throughout action observation and execution conditions, this activity is not consistently found in the same specific brain regions across different studies[13]. However, researchers have found that the observation of hand movements specifically induces the response of mu desynchronization in the right hemisphere[44]. The same pattern was found for facial imitation tasks[45,46] and performing an action using one's hand, such as a button press or a toy grasp[40]. Additionally, the magnitude of desynchronization was found to be stronger in studies that investigated social bonding compared to action understanding. This likely occurred due to the different imitative contexts the infant was subject to[40], suggesting that the extent to which the neural mirroring system is activated and the brain regions it is found in depends on the nature of the imitative task (e.g. motor behavior or social behavior). However, although there are inconsistencies in the specific brain regions that are being activated when mu desynchronization is detected, this does not invalidate the notion that an underlying neural mirroring system likely exists in humans to facilitate imitation. This is supported by the evidence that mu desynchronization is specific to interactions between action observation and execution seen during imitation[47]. Rather, such inconsistencies can be accounted for by the specific procedure employed by researchers when they place infants in imitative contexts (e.g.

Table 1 Major EEG Findings in Infant Imitation Studies

Studies	Major findings
Marshall et al. (2011)	During action execution, mu desynchronization was detected at central electrode sites; during action observation conditions, mu desynchronization was in central, frontal and parietal electrode sites
Southgate et al. (2009)	Found mu desynchronization in both action observation and execution conditions, and detected this signal when infants began to anticipate the approaching action during observation conditions
Debnath et al. (2018)	Discovered mu desynchronization during action observation and execution, as well as during the onset of the observed action; in both conditions, this was detected over frontal, central, parietal, and occipital electrode sites
Warreyen et al. (2012)	During action execution, the strongest mu desynchronization was found over central electrode sites; during action observation, mu desynchronization was more distributed across frontal and parietal regions.
Saby et al. (2012)	Detected mu desynchronization during action execution, action observation when the infant's prior movement was imitated by the experimenter, and when the infant began to anticipate the experimenter's upcoming action.
Reid et al. (2011)	Mu desynchronization was most significantly detected in dyadic interactions, when infants were engaged in a face-to-face imitative game.

the order of action observation and execution conditions), as well as the limitations in using EEG as a method to study infant cognition, which will be further discussed below under Limitations and Improvements.

2 **Attention as a cognitive property of the neural mirroring system**

Because mu desynchronization was found to be broadly distributed over electrode sites during action observation[21,39], it is believed that on top of the neural mirroring system, an attention process is also involved when viewing movements[36]. This is supported by studies that found how individual mirror neurons can extend to frontal and parietal areas[10,48]. In addition, Warreyen et al. (2012) found that in their observation conditions, there was also significant suppression in rhythms originating in occipital regions, suggesting the involvement of an attentional component. This can be explained by the infants' awareness that they have to imitate the observed action from the second or third trial onwards, and may therefore have been more attentive to the presentation. Moreover, mu desynchronization was significantly detected when 8-11-months old infants played a peek-a-boo game which required continual attention[49]. These results suggest that aside from motor activity alone when observing actions, the neural mirroring system is also associated with attention. In addition, because of the flexible nature and different imitative contexts of the neural mirroring system, there are likely many other cognitive properties that underlie its activity, which remain to be further investigated.

Limitations and Improvements

Overall, although the aforementioned EEG studies have suggested that a neural mirroring system becomes active in infants when they are engaged in imitative tasks, there are still several limitations in this area of research that must be considered before arriving at a definitive conclusion. Three primary limitations in the mirror neurons field include 1) the use of EEG to study infant cognition 2) lack of evidence demonstrating how the neural mirroring system changes as an infant develops motor skills and 3) the lack of up to date research.

Despite there being a restraint to the brain-imaging techniques that can be used on infants due to ethical concerns, such as their higher susceptibility to being affected by the strong magnetic fields or radiation effects of some techniques, it is important to recognize that there are several drawbacks to using EEG as a method for studying infant cognition.

Firstly, EEG is a technique that lacks spatial specificity[21], so detecting overlaps in mu desynchronization during action observation and execution does not necessarily mean that only visual and motor brain areas were activated. Although Fox et al. (2016) conducted a meta-analysis of 85 studies and found that mu desynchronization is an appropriate index for measuring activity of a mirroring system, according to Hobson and Bishop (2016), there are concerns about the interchangeability between mu rhythm desynchronization and visual alpha desynchronization as they occur at similar frequencies. Visual alpha desynchronization is believed to be linked to visual attention when responding to a visual stimulus. However, according to Bowman et al. (2017), it is probable that both the attention resulting from the response to a visual stimulus, as well as mirroring processes, occur simultaneously when an action is being observed. While the infant EEG studies in this paper determined that mu desynchronization was specifically detected during action observation and execution, one major confound in interpreting this type of neural activity in future studies is the presence of other rhythms.

Secondly, limited evidence exists on how mu rhythm changes as infants gain new motor abilities. While active during motor skills, its developmental trajectory remains undetermined. Although some studies, such as Paulus et al. (2012), have explored this, the evidence is insufficient for definitive conclusions. Paulus et al. (2012) found reduced mu rhythm activity (6-8 Hz) in infants after rattle-shaking training, correlating with training intensity. However, this study lacked several measures: mu rhythm during action execution, infant motor skill proficiency, and a resting baseline comparison. Future research should investigate mu rhythm changes as infants gain new motor skills to further understand how the neural mirroring system facilitates infant to early childhood development.

Finally, even though studies investigating mirror neurons have made significant advancements, another limitation lies in the fact that this field of research is predominantly no longer recent. Therefore, more up-to-date research may potentially reveal additional insights into the role of mirror neurons in imitation. Additionally, most studies are limited to studying participants of Western backgrounds, investigating general forms of imitation, such as automatic imitation (the tendency to unconsciously replicate observed actions and behaviors), or intentional imitation (mimicking observed actions with a goal and being resistant to imitating all observed actions)[50]. Further exploring how imitation may manifest in infants differently across cultures (e.g. some parents encouraging children to mostly imitate through observation and inference instead of direct instruction) may provide insights into the universality of the neural mirroring system in infants.

Conclusion

Overall, the current evidence suggests that a neural mirroring system is involved in imitation by facilitating understanding the actions of others as well as social bonding during dyadic interactions. However, the exact circuitry and mechanisms behind the neural mirroring system when it facilitates those processes is still unknown.

The findings in this paper can provide the basis for potential clinical applications, such as early detection of developmental disorders or social communication difficulties in infants.While the relationship between mirror neuron dysfunction and neuropsychiatric conditions like autism is debated[47], researchers can conduct similar EEG methodologies with action observation-execution conditions on infants with autism to observe potential differences in mu rhythms. Such differences may prompt further investigation of the role of mu desynchronization in the neural mechanisms associated with early developmental delays.

Another area of application for the findings in this paper is the educational industry. Researchers could further explore how motor and social skills are developed over time in infants through imitation, and investigate whether mu desynchronization persists as the infant acquires such skills. Because imitation is an integral aspect of learning[51], educators could adapt these EEG study methodologies for infant educational environments, such as nurseries, to promote motor and social development.

The current findings in the field of mirror neuron research and infant imitation highlight the unique biological nature of a seemingly simple behavior that manifests at a young age and progresses throughout one's lifetime as they mature. Imitation is a fascinating behavior because it is the fundamental means of learning and communication before language emerges[52]. Therefore, investigating the neural mirroring system in an infant's brain when they imitate others' actions and behavior can reveal important insights into how humans develop a sense of the world around them and social connections that are crucial to one's well-being and identity.

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