A Frontal Account of False Alarms

Sara B. Festini1 and Benjamin Katz2

Abstract

Prior research has demonstrated that the frontal lobes play a critical role in the top–down control of behavior, and damage to the frontal cortex impairs performance on tasks that require executive control (e.g., Burgess & Stuss, 2017; Stuss & Levine, 2002). Across executive functioning tasks, performance deficits are often quantified as the number of false alarms per the total number of nontarget trials. However, most studies of frontal lobe function focus on individual task performance and do not discuss commonalities of errors committed across different tasks. Here, we describe a neurocognitive account that explores the link between deficient frontal lobe function and increased false alarms across an array of experimental tasks from a variety of task domains. We review evidence for heightened false alarms following frontal deficits in episodic long-term memory tests, working memory tasks (e.g., n-back), attentional tasks (e.g., continuous performance tasks), interference control tasks (e.g., recent probes), and inhibitory control tasks (e.g., go/no-go). We examine this relationship via neuroimaging studies, lesion studies, and across age groups and pathologies that impact the pFC, and we propose 11 issues in cognitive processing that can result in false alarms. In our review, some overlapping neural regions were implicated in the regulation of false alarms. Ultimately, however, we find evidence for the fractionation and localization of certain frontal processes related to the commission of specific types of false alarms. We outline avenues for additional research that will enable further delineation of the fractionation of the frontal lobes’ regulation of false alarms.

INTRODUCTION

False alarms are a common type of error that occurs when an individual mistakenly responds to indicate that a signal is present when they should have withheld their response because the signal is, in fact, absent. These errors, also referred to as “false positives,” frequently occur in daily life. For instance, a person waiting to make a left turn at a traffic signal might remove their foot from the brake when the green light appears for the through-lanes of traffic, even though the turn arrow is still red. In a different context, it is possible for someone to greet a person with enthusiasm only to later realize that the individual is a stranger rather than a well-known friend. These are both examples of false alarms that reflect inaccurate behaviors in response to external stimuli. Because these errors disrupt performance across a wide variety of contexts, it is beneficial to minimize their occurrence.

In this review, we discuss evidence that the frontal lobes of the brain are heavily involved in the regulation of false alarms. We also consider whether discrete regions of the frontal lobes are differentially implicated in false alarm commission across different cognitive domains. Because the variety of contexts in which false alarms can occur is vast (e.g., memory tasks, attention tasks, response inhibition tasks), much of the literature on false alarms is separated by the task domain. In an effort to provide a more comprehensive, integrative account, we review evidence for heightened false alarm rates following various frontal lobe deficits across a large array of experimental tasks. Specifically, we summarize research on the frontal lobes’ involvement in false alarm regulation in (a) episodic long-term memory tests, (b) working memory tests, (c) attentional tasks, (d) interference control tasks, and (e) inhibitory control tasks. Our goal is to describe sources of overlap as well as distinctions between regions of the frontal lobe that are involved in the regulation of false alarms depending on the task context. We also identify and discuss 11 explanations for false alarms because of specific types of errors in cognitive processing (e.g., deficient postretrieval monitoring, inability to maintain task goals) and how these processing errors have the potential to inflate false alarms on a wide variety of tasks.

FRONTAL LOBES: ANATOMY, FUNCTION, AND HISTORY

Frontal Lobe Anatomy

The frontal lobes are the most rostral regions of the brain and the latest to develop (Fuster, 2015; Stuss & Knight, 2013). Evidence has also documented that the frontal lobes are highly interconnected within themselves and with other regions of the brain (see Fuster, 2015; Yeterian, Pandya, Tomaiuolo, & Petrides, 2012; Pandya & Yeterian, 1996). Subcortically, many of the afferent projections to the pFC, the most anterior portion of the frontal lobes, arrive from

1University of Tampa, 2Virginia Tech
the dorsomedial nucleus of the thalamus, relaying information from a variety of regions, including the amygdala, temporal cortex, substantia nigra, and cerebellum (Fuster, 2015). Other afferent projections to the pFC arrive from the amygdala, hypothalamus, pons, tegmentum, cerebellum, and hippocampus (Fuster, 2015). Cortical projections have been documented between the pFC and nonprimary visual, auditory, somatosensory, and paralimbic brain regions (Fuster, 2015; Yeterian et al., 2012), indicative of the fact that the frontal lobes regulate information across sensory and emotional domains. Evidence indicates that nearly all prefrontal afferents have reciprocal efferents, and additional prefrontal efferents are sent to motor regions, including the BG (Fuster, 2015), which allows the pFC to provide regulatory input over behavior.

**Frontal Lobe Function**

Functionally, the frontal lobes help us act appropriately given the current environmental context and task goals (e.g., see Reuter-Lorenz, Festini, & Jantz, 2016; Stuss & Knight, 2013; Stuss & Levine, 2002). For instance, while in a movie theater, we know it is socially inappropriate to answer a phone call, and we may have to inhibit the natural tendency to pick up our phone when it vibrates. Or, while searching for a friend in a crowd, we have to ignore distracting information and only wave to the person that we know. Such higher level regulatory control over our behavior has been termed “executive functioning.” Nevertheless, the general term, “executive functioning,” encompasses a large array of complex, regulatory processes, such as maintaining task goals, prioritizing, planning, ignoring distractors, updating working memory, switching attention, managing interference, and stopping unnecessary behaviors.

**Donald Stuss: A Trailblazer in Frontal Lobe Research**

Much of Donald Stuss’ research was devoted to understanding frontal lobe function and effects of frontal lobe damage. Within his capacity as a neuropsychologist, Stuss published numerous neuropsychological assessments of frontal lobe function that were critical to better understanding the complexities of executive functioning and the frontal lobe (e.g., Alexander, Stuss, & Gillingham, 2009; Floden & Stuss, 2006; Stuss, Binns, Murphy, & Alexander, 2002; Stuss, Bisschop, et al., 2001; Stuss, Floden, Alexander, Levine, & Katz, 2001; Stuss et al., 1998, 2000). Stuss noted that neuropsychological frontal tasks were used in an overly broad fashion. Importantly, Stuss and colleagues explained that “the effects of lesions in different regions should not be blended into a single ‘executive’ account” (Alexander et al., 2009, p. 1432). Or, to put it more succinctly, “there is no ‘prefrontal cortex syndrome’” (Burgess & Stuss, 2017, p. 760).

Furthermore, Stuss proposed a need to differentiate functions of specific subregions of the pFC. “The frontal lobes clearly are not homogenous anatomical or functional monolithic structures, but are composed of morphologically distinct areas interconnected with each other…” (Stuss, Alexander, et al., 2002, p. 404). Although Stuss offered that terms like “executive control” might be “convenient labels to represent the sum of the processes recruited at any moment, for any task,” he also worked to highlight the importance of discriminating between different processes and associated frontal regions (Stuss et al., 2002, p. 404).

Stuss argued that the frontal lobes “may be what define us as human” (Stuss & Levine, 2002, p. 402). Overall, Stuss promoted the detailed and sophisticated analysis of errors related to the operations of the frontal lobe (Stuss, Murphy, Binns, & Alexander, 2003; Stuss, Binns, et al., 2002). These error analyses supported and expanded this view of different anatomical and functional specificity. For example, one of Stuss’ reviews of lesion studies suggested three separable attentional systems (Stuss, Binns, et al., 2002). Stuss reminds us that terms like “failure to inhibit responses” represents “surface descriptions of error types more than basic processes” (Stuss et al., 2003, p. 2377).

Whether referred to as false alarms, false positives, failure to inhibit responses, or errors of commission,1 this particular error type remains a focal point of analysis in executive function research. However, it has rarely been considered in a systematic fashion across multiple tasks. Given Stuss’ suggestion that “error analysis can be considered an indirect reflection of control mechanisms” and the continuing interest in error variables in executive function research (Stuss et al., 2003, p. 2376), the time is ripe for a review that investigates the extent to which the cognitive and neural processes involved in false alarms are themselves shared—or separable.

**Sources of Frontal Lobe Inefficiency**

Many factors can disrupt frontal lobe functioning. Damage to the frontal lobe as the result of a stroke, tumor, or other traumatic brain injury has been an important source of information regarding frontal lobe function (e.g., Stuss & Levine, 2002). Such research on the effects of frontal lobe lesions provides causal evidence for the specific deficits that result from focal damage, and much research cited in this review utilizes the findings from this important neuropsychological lesion data. Nonetheless, as lesions are naturally occurring and not restrained to circumscribed brain regions, it is necessary to consider lesion data in conjunction with behavioral and neuroimaging data.

The pFC has been found to be one of the main locations of age-related deficits based on structural, functional, neuropsychological, and experimental cognitive evidence (e.g., Reuter-Lorenz & Grady, 2013; Turner & Spreng, 2012; Raz, Ghisletta, Rodrigue, Kennedy, & Lindenberger, 2010; Solbakk et al., 2008; West, 1996; Moscovitch & Winocur, 1992, 1995). Both prefrontal gray and white matter show age-related declines (e.g., Salat et al., 2004,
2005). Furthermore, older adults tend to show larger age-related performance declines on executive functioning tasks relative to nonexecutive tasks (Reuter-Lorenz et al., 2016; Verhaeghen, 2011). Relating structure to function, a meta-analysis performed on healthy aging samples also found that larger pFC volume predicted superior executive functioning (Yuan & Raz, 2014). Nevertheless, it is also important to remember that there is considerable variability between individuals, and some older adults exhibit less executive function decline (e.g., Goh, An, & Resnick, 2012; de Frias, Dixon, & Strauss, 2009). Age-related variation in executive performance is also considered as a source of frontal lobe inefficiency that may give rise to heightened false alarms.

As the frontal lobes are not fully developed until adulthood (e.g., Stuss & Knight, 2013), children's elevated false alarms may be partly accredited to inefficient frontal lobe function (e.g., Levin et al., 1991; Schacter, Kagan, & Leichtman, 1995). For instance, children showed a drop in false alarms on a go/no-go task from the ages of 7 to 12 years (Levin et al., 1991), and older children often show reduced susceptibility to misinformation (Brainerd & Reyna, 1998). Parkin (1997) proposed that research into adult frontal neuropsychology would be applicable to better understanding childhood behavior, as both share frontal inefficiencies.

Converging evidence from attention-deficit/hyperactivity disorder (ADHD) research also underscores the role of frontal regions in one's likelihood of making errors of commission, particularly in the context of inhibitory control and attentional control tasks. Hypoactivation has been observed in children and adults with ADHD, primarily in frontoparietal networks associated with executive function performance (Cortese et al., 2012). Furthermore, substantial differences have been observed in children with and without ADHD in the number of false alarms on continuous performance tasks (CPTs), and medication generally results in a substantial reduction in errors of commission (and often, it should be noted, errors of omission as well; Losier, McGrath, & Klein, 1996). Additionally, in some of our own work, we have found commission error rates among children with ADHD sensitive to intervention through cognitive training (Jones, Katz, Buschkuehl, Jaeggi, & Shah, 2020).

Schizophrenia is also associated with frontal deficits. The hypofrontality hypothesis of schizophrenia states that individuals with schizophrenia underactivate the frontal cortex (e.g., Hill et al., 2004; Kaneko et al., 2017). Enlarged ventricles (e.g., Kempton, Stahl, Williams, & DeLisi, 2010) and less gray matter (e.g., Yuksel et al., 2012) are also observed in schizophrenia, which can impact the frontal lobe. Some symptoms of schizophrenia, such as delusions, working memory deficits, and disorganized thought, may be due to these differences in the frontal lobes (Kuperberg & Heckers, 2000; Liddle & Morris, 1991). As such, where appropriate, we also consider the effects of schizophrenia on false alarms.

FALSE ALARMS
Defining False Alarm Errors
False recognition errors fall within the category of false alarms because they occur when previously unlearned memoranda are mistakenly endorsed. Early signal detection research, though initially grounded in the advent of new electronic technologies (such as radar), commonly used recognition memory tests to classify false alarms. Many of the first experiments in this space did not measure false alarms specifically, however (Wixted, 2020). John Swets likely deserves much of the initial credit for the proliferation of the study of this type of error: He specifically advocated for including sufficient numbers of “catch trials” that did not include a signal, and furthermore, he suggested explicitly asking participants to try and avoid making “false-positive” responses (Swets, 1961; Tanner & Swets, 1954).

Here, we specifically define false alarms as the inaccurate commission of a response, indicating that a given stimulus or signal is present, when the response should have been withheld because the signal is absent according to task instructions. As such, for example, false alarms can occur in episodic long-term memory and working memory tests when participants misjudge a newly presented item as a previously studied item; in attentional tasks, like the CPTs, when participants endorse nontargets even though the appropriate stimulus features of the target are absent; in interference control tasks, like the recent probes task, when familiar recent memoranda are mistakenly affirmed; and in inhibitory control tasks, such as when participants inaccurately respond on no-go trials. Of course, we also note that ample research documents a myriad of other erroneous behaviors that result from frontal lobe damage (e.g., difficulty with planning, sequencing, set shifting, strategic memory retrieval, overcoming perseveration, prepotent response inhibition, resolving interference among competing memory representations, etc.). Although these errors may share some neural or cognitive mechanisms with false alarm errors, our focus in this article is specifically on the commission of false alarms in the absence of a true signal.

Multiple Pathways through Which False Alarms May Occur
False alarms are the behavioral manifestations of errors in cognitive processing. Although the inaccurate false alarm behavior can be classified based on the objective comparison to the appropriate behavior, the source of a false alarm error is more complex. There are multiple reasons through which false alarms may occur, each of which may disrupt cognitive processing sufficiently to result in an error of commission. Below, we posit 11 distinct, but not necessarily orthogonal, sources of false alarms, including (1) difficulty maintaining task goals, (2) failure of stimulus–response mapping, (3) response selection difficulty, (4) deficient sensory processing, (5) deficient prepotent response
depending on task demands. For instance, poor item-specific recollection or familiarity, (10) deficient post-retrieval monitoring, and (11) poor metacognition. Again, we note, however, that these sources are not mutually exclusive. A manifold of issues may potentially contribute to the commission of a single false alarm error, and some cognitive errors may not be independent from one another depending on task demands. For instance, poor item-specific recollection may exacerbate or contribute to poor interference resolution. Nevertheless, certain tasks have fewer possible contributing factors because, for instance, memory processing is not required for all cognitive tasks. Table 1 summarizes which sources of false alarms are likely for each task domain, and detailed examples are provided for a recognition memory task (Figure 1) and for a go/no-go task (Figure 2). The below descriptions briefly summarize the reasons through which false alarms may occur, with additional detail provided within the task-separated sections.

**Difficulty Maintaining or Following Task Goals**

False alarms can be made if an individual has difficulty comprehending the requirements of the task. Frontal lobe damage can manifest in general planning deficits and difficulty understanding or implementing complex rules (e.g., Gouveia, Brucki, Malheiros, & Bueno, 2007; Shallice & Burgess, 1991; Luria, 1966), and the false alarms that occur may reflect this general task misunderstanding or difficulty executing task goals. Stuss noted that frontal damage could result in an “inability to regulate behavior according to internal goals and constraints” (Stuss & Levine, 2002, p. 418), and this is one source of false alarms.

**Failure of Stimulus–Response Mapping**

Similarly, if someone is unable to maintain the appropriate stimulus–response mapping (i.e., which button to press to indicate which response), a false alarm can be committed. Stuss referred to this process as “task setting” and ascribed it to the left lateral frontal cortex (e.g., see Burgess & Stuss, 2017; Stuss & Alexander, 2007).

**Response Selection Difficulty**

Errors in a related, but arguably distinct, process of response selection can also cause false alarms. When performing cognitive tasks, participants often must decide which response to indicate in an effort to follow the task rules given the current task context and stimulus characteristics. Response selection difficulty following left frontal damage has been proposed to contribute to false alarms on go/no-go tasks (Arbula et al., 2017) and attentional tasks (e.g., choice RT; Stuss, 2006; Stuss et al., 2005), for example.

**Deficient Sensory Processing**

Deficient sensory processing can also muddle the quality of incoming stimuli and disrupt behavior. For example, if an individual cannot see the stimulus that is presented in high detail, a false alarm could occur on a memory test for a perceptually similar foil. This type of error would reflect a sensory deficit rather than an executive one. For this reason, many assessments of executive function require normal or corrected-to-normal vision (or hearing for auditory stimuli) to participate.

**Deficient Prepotent Response Inhibition**

For tasks that require the quick inhibition of behavior (e.g., go/no-go tasks), deficient prepotent response inhibition is often proposed as the source of the false alarm. Response inhibition requires that individuals stop an already initiated motor program, and there are individual differences in the ability to execute this prepotent response inhibitory control (Garavan, Hester, Murphy, Fassbender, & Kelly, 2006). Frontal lobe damage has been proposed to disrupt this process and heighten false alarms on such tasks. For example, in one study by Picton, Stuss, and colleagues, patients with lesions to the left superior portion of Brodmann’s area 6 demonstrated a greater number of false alarms on a go/no-go task versus individuals without frontal lesions (Picton et al., 2007). Although several underlying cognitive and neural mechanisms may individually or collectively contribute to these differences in performance, including issues with stimulus–response mapping and monitoring, it is also possible that deficiencies in inhibitory motor control more generally play a key role in false alarm regulation, particularly in, for example, adult individuals with ADHD (Barkley, 1999).

**Deficient Interference Resolution**

Certain tasks require participants to evaluate and overcome interference that is induced within the task. For instance, familiarity-based interference can be introduced in working memory tasks, in which recently studied foils are presented as memory probes as opposed to currently studied items (e.g., Festini & Reuter-Lorenz, 2014; Berman, Jonides, & Lewis, 2009). In these cases, participants must overcome the familiarity-based interference to correctly respond. This interference control process often results in lengthened RTs, or false alarm errors (e.g., Festini & Reuter-Lorenz, 2014; Atkins, Berman, Reuter-Lorenz, Lewis, & Jonides, 2011). The left inferior frontal gyrus (IFG), left ventrolateral pFC (VLpFC), and left anterior pFC (APFC) have been proposed to be important to overcome familiarity-based interference (e.g., Nelson, Reuter-Lorenz, Persson, Sylvester, & Jonides, 2009; Nee, Jonides, & Berman, 2007). Associative interference can also occur when semantically similar memoranda compete in memory (Unsworth, 2019; Gallo, 2013). False memories can result if the interference control process fails (e.g., Atkins et al., 2011; Atkins &
Table 1. Primary and Contributing Sources of False Alarms by Test Domain

<table>
<thead>
<tr>
<th>Test Domain</th>
<th>Poor Maintenance of Task Goals</th>
<th>Stimulus–Response Mapping Errors</th>
<th>Response Selection Difficulty</th>
<th>Deficient Sensory Processing</th>
<th>Poor Strategic Encoding</th>
<th>Lapse in Sustained Attention</th>
<th>Deficient Postretrieval Monitoring</th>
<th>Deficient Interference Resolution</th>
<th>Deficient Item-specific Recollection/Familiarity</th>
<th>Poor Metacognition</th>
<th>Deficient Prepotent Response Inhibition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Episodic long-term memory</td>
<td>C</td>
<td>C</td>
<td>P</td>
<td>P</td>
<td>C</td>
<td>C</td>
<td>P</td>
<td>C</td>
<td>P</td>
<td>P</td>
<td>C</td>
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<tr>
<td>Working memory</td>
<td>C</td>
<td>C</td>
<td>P</td>
<td>C</td>
<td>P</td>
<td>C</td>
<td>P</td>
<td>C</td>
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<td>P</td>
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<tr>
<td>Attention</td>
<td>C</td>
<td>C</td>
<td>P</td>
<td>C</td>
<td>P</td>
<td>C</td>
<td>P</td>
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<tr>
<td>Interference control</td>
<td>C</td>
<td>C</td>
<td>P</td>
<td>C</td>
<td>P</td>
<td>C</td>
<td>P</td>
<td>C</td>
<td>C</td>
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<tr>
<td>Inhibitory control</td>
<td>C</td>
<td>C</td>
<td>P</td>
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<td>P</td>
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</tbody>
</table>

A “P” denotes that the cognitive processing error is a primary source of a false alarm for the test domain, whereas a “C” denotes that the cognitive processing error is an additional possible contributing source of a false alarm. A blank cell indicates that the processing error is unlikely to be a source of a false alarm for that test domain. Designations are not definitive and may vary by task/context: episodic long-term memory tasks (e.g., long-term recognition memory tests), working memory (e.g., n-back, Sternberg item recognition), attention (e.g., continuous performance task, ROBBIA), interference control (e.g., recent probes, false memory), and inhibitory control (e.g., go/no-go).
Reuter-Lorenz, 2008), and neuroimaging evidence indicates that the pFC is associated with overcoming interference (Bowman & Dennis, 2015; Atkins & Reuter-Lorenz, 2011). For example, Atkins and Reuter-Lorenz (2011) found greater dorsal lateral pFC (DLPFC) activity when participants correctly rejected related lures, whereas greater left mid-VLPFC activity was associated with greater behavioral evidence of semantic interference.

**Lapses in Sustained Attention**

Accurate performance in CPTs or other tasks of sustained attention require that participants maintain focus on a stream of stimuli for an extended period of time. False alarms may occur if participants exhibit lapses in sustained attention, where they miss cues and respond without complete information. Studies of visual sustained attention, for example, have found that image degradation increases the number of false alarms (Duchmore, Parasuraman, & Jiang, 1983). It is also possible, in lengthier sustained attention tasks, that participants may develop specific strategies to avoid making false alarms (Sarter, Givens, & Bruno, 2001).

**Poor Strategic Encoding**

False alarms may also result from weak memory representations because of poor strategic encoding. Inefficient frontal lobe function may hinder one’s ability to strategically engage in deep processing (Parkin, Ward, Bindschaedler, Squires, & Powell, 1999; Parkin, 1997; Moscovitch, 1992; Craik & Lockhart, 1972), which can result in less-detailed memory representations. Because the memory representations are weaker, susceptibility to false alarms will be heightened. Alexander, Stuss, and Fansabedian (2003) observed that patients with frontal lesions had inefficient strategy use, such that they did not subjectively organize the learned information as well as control participants. Stuss et al. (1994) also documented deficient organizational strategies in patients with frontal lobe damage. Moscovitch (1992) posited that the frontal lobes in particular are necessary for strategic encoding (and retrieval). He explains that the frontal lobes allow learning to become goal-directed, rather than reflexive.

**Poor Item-Specific Recollection or Familiarity**

Recollective memory processes also require a degree of executive control (e.g., Hedden & Yoon, 2006; Moscovitch,
1992). Some patients with frontal lobe damage have been shown to exhibit more false alarms when item-specific recollection is necessary (Verfaellie, Rapcsak, Keane, & Alexander, 2004). That is, when there is heightened familiarity between a foil and a target, participants must rely on detail- and context-oriented recollective processes, as opposed to relying on gist-based memory driven by familiarity. Greater reliance on familiarity and impoverished memory representations can increase false alarms.

One lesion study in rats demonstrated that recollective recognition relied on the medial pFC (Farovik, Dupont, Arce, & Eichenbaum, 2008), and lesion studies in humans indicate that the DLPFC is crucial for successful recollection-based memory (e.g., Alexander et al., 2003; Janowsky, Shimamura, & Squire, 1989b). Curran, Schacter, Norman, and Galluccio (1997) also attributed heightened false alarms in recognition memory following right frontal damage to an increased reliance on general similarity and vague memory (see also Schacter, Curran, Galluccio, Milberg, & Bates, 1996). Nonetheless, lateral pFC lesions have also been shown to impair familiarity (Aly, Yonelinas, Kishiyama, & Knight, 2011), which could also affect false alarm performance.

Deficient Postretrieval Monitoring

Postretrieval monitoring involves appraising whether currently retrieved memory representations match the current task demands (e.g., Festini & Reuter-Lorenz, 2015; Cruse & Wilding, 2009; Achim & Lepage, 2005). False alarms can result from dysfunctional postretrieval monitoring when individuals frequently misjudge that the current memory representation was previously encountered or is relevant to the present task. ERP evidence suggests that right prefrontal activity is associated with postretrieval monitoring (Cruse & Wilding, 2009), and fMRI evidence supports the role of the DLPFC in postretrieval monitoring during both item recognition (i.e., old/new memory judgments) and associative recognition (i.e., intact/rearranged pair judgments; Achim & Lepage, 2005).

The frontal lobes are also implicated in source monitoring, which requires attributing a memory to the correct context (e.g., male or female voice, movie or real life). Poor source monitoring can similarly increase false alarms. Patients with frontal lesions have frequent source monitoring deficits (Ward & Parkin, 2000; Parkin, 1997; Janowsky et al., 1989b),
as do older adults (Balota et al., 1999; Dywan & Jacoby, 1990), who can suffer from frontal lobe dysfunction (e.g., West, 1996; Moscovitch & Winocur, 1995). Although postretrieval monitoring may be linked to metacognitive errors, we consider it separately because it receives considerable discussion in the literature.

**Poor Metacognition**

Metacognition refers to an awareness of one’s own cognitive abilities, including the ability to accurately predict future memory performance (i.e., metamemory, Koriat, 2007). Janowsky, Shimamura, and Squire (1989a) documented that individuals with frontal lesions had inferior feeling of knowing accuracy relative to matched control participants (see also Parkin, 1997).

Given the higher level nature of metacognition, there are multiple possible metacognitive impairments that can potentially provoke false alarms. For instance, impairments in metacognition can contribute to false alarms because they may result in poorer strategic encoding. If people are unaware that it will be difficult for them to remember certain information in the future (because of poor metamemory), they will not implement metacognitive control operations to try to improve their memory (e.g., by taking steps to devote more study time to the items; Koriat, 2007), and greater false alarms can result. Luria (1966) reported that frontal dysfunction resulted in inaccurate predictions of future memory performance, even after practice with the task, as well as an inability to devote additional study time to previously forgotten words.

**EVIDENCE OF FRONTAL REGULATION OF FALSE ALARMS ACROSS DIFFERENT TASK DOMAINS**

**Episodic Long-Term Memory Tests**

**False Recognition**

Recognition memory deficits have been observed in individuals with frontal damage (Alexander et al., 2003, 2009; Verfaellie et al., 2004; Ward & Parkin, 2000; Swick & Knight, 1999; Parkin, Bindschaedler, Harsent, & Metzler, 1996; Schacter et al., 1996; Stuss et al., 1994). Although recognition requires less frontal control than recall, Stuss and Levine (2002) explain, “Contrary to clinical lore, recognition was also affected by frontal damage” (p. 411). We specifically consider false recognition errors because false recall is not necessarily a false alarm. By our definition, false alarms are committed in response to or in anticipation of a stimulus, whereas false recall involves self-generated responses. Nevertheless, importantly, not all individuals with frontal lesions have elevated false recognition/false alarms, as variability in performance has been noted (Alexander et al., 2009; Verfaellie et al., 2004; Janowsky, Shimamura, Kritchevsky, & Squire, 1989).

In a list-learning paradigm, patients with frontal damage exhibited significantly heightened false alarms on recognition memory tests relative to controls (Alexander et al., 2009). Parkin et al. (1996) describe a case study with left frontal lobe damage following rupture of the anterior communicating artery, whose false alarm rates exceeded those of control participants by over 15 standard deviations—exceptionally high levels (see also Ward & Parkin, 2000; Parkin et al., 1999; Parkin, 1997). Alexander et al. (2005) also found a significant false alarm effect on the recognition memory component of the California Verbal Learning Test that was specific to patients with left dorsolateral frontal damage. A different case study with a patient with damage to the right frontal lobe also exhibited extremely high false recognition across a wide variety of stimuli, including visually presented words, auditorily presented words, pictures, sounds, and pseudowords (Schacter et al., 1996). These false alarm rates were more than twice those of control participants. This same patient gave frequent aberrant “remember” judgments in remember-know paradigms (Curran et al., 1997; Schacter et al., 1996). Heightened “remember” judgments may be due to right frontal damage (Schacter et al., 1996), as Parkin et al.’s case study with left frontal damage provided false recognition with “familiar” judgments. Critically, these false alarms were not simply guesses because his hit rate exceeded his false alarm rate (Schacter et al., 1996). Schacter et al.’s (1996) extensive assessment of patient B. G. also revealed that the false alarms were not solely because of shared semantic or perceptual similarity of targets and foils—false alarms could occur for unrelated items; nonetheless, B. G.’s false alarms could be reduced by presenting foils from non-studied categories.

Experimental lesions in rats have similarly indicated that damage to the pFC increases false alarms (Eichenbaum, Fortin, Sauvage, Robitsek, & Farovik, 2010). Specifically, assessments of receiver operating characteristic curves in rats with medial prefrontal lesions demonstrated that they exhibited more false alarms, whereas rats with hippocampal lesions exhibited fewer hits rather than a particularly increased number of false alarms (Eichenbaum et al., 2010). Thus, Eichenbaum et al. (2010) interpret this behavior to indicate that prefrontal damage results in greater reliance on familiarity as opposed to recollection.

Importantly, heightened false recognition is observed in normal aging (Murphy, West, Armilio, Craik, & Stuss, 2007), which is broadly consistent with the frontal hypothesis of cognitive aging (e.g., Moscovitch & Winocur, 1995; West, 1996). Greater reliance on familiarity in normal aging (e.g., Daselaar, Fleck, Dobbins, Maiden, & Cabeza, 2006; Prull, Dawes, Martin, Rosenberg, & Light, 2006) has also been proposed as one mechanism that may explain elevated false alarms on recognition memory tasks in older adults. Nevertheless, neural correlates of recollection and familiarity have been found to be reduced in older adults (Duarte, Graham, & Henson, 2010). Duarte et al. (2010) instead propose that greater false recognition with age is
due weakened recollection and weakened familiarity, which result in greater difficulty distinguishing between accurate and inaccurate memory representations.

**Working Memory Tasks**

*n*-Back with Lures

The *n*-back task is commonly used to assess working memory ability and requires that participants decide if the current stimulus matches the one that they encoded a particular number (*n*) of trials previously. Researchers can increase the difficulty of the task by including lure trials of stimuli that were presented *n* ± 1 trials previously, and lure trials have been shown to induce more false alarms (e.g., Kane, Conway, Miura, & Colflesh, 2007). Evidence indicates that the pFC helps regulate performance on this task. For example, genetic influences of prefrontal dopaminergic activity have been found to affect susceptibility to false alarms for lure *n*-back trials (Smith, Swift-Scanlan, & Boettiger, 2014). Older adults have also shown elevated false alarms (Gajewski & Falkenstein, 2014), particularly for lure trials on the *n*-back task (Schmiedek, Li, & Lindenberger, 2009). Gajewski and Falkenstein (2014) further noted delayed and reduced frontal ERP components in older adults, suggesting that age-related frontal dysfunction was central to the commission of these errors. Comparable ERP deficits were observed in individuals with ADHD, along with worse sensitivity (*d'*) on lure *n*-back trials (Stroux et al., 2016). Whereas control participants showed higher amplitude N200 components for lure relative to nonlure trials, participants with ADHD did not show such modulation (Stroux et al., 2016).

Neuroimaging studies have also documented variability in frontal lobe activity on the *n*-back task in frontal-compromised samples. For instance, alcoholics exhibited reduced bilateral DLPFC fMRI activity while performing a spatial *n*-back, although there were no behavioral differences in false alarms (Pfefferbaum et al., 2001). Moreover, even before alcohol dependence, adolescents with a family history of alcoholism showed reduced frontal activity on the *n*-back task relative to controls, including reductions in the left DLPFC and right APFC, IFG, and cingulate cortex activity (Cservenka, Herting, & Nagel, 2012). However, again, behavioral false alarm differences were not observed (Cservenka et al., 2012). Finally, individuals with schizophrenia exhibited greater errors of omission but did not show false alarm differences on the *n*-back task (Royer et al., 2009), although the frequency of lure trials was not manipulated. In this experiment, individuals with schizophrenia had greater activity in the left superior frontal sulcus, left frontal pole, and bilateral posterior parietal cortex for 2-back versus 0-back trials (Royer et al., 2009). Hence, differences in frontal activation during the regulation of false alarms have also been observed in individuals with frontal lobe inefficiencies, even when there are no behavioral differences in false alarm errors.

**Sternberg Item Recognition**

Working memory performance is also commonly assessed with the Sternberg item recognition test (Sternberg, 1966), in which participants must maintain a small set of memoranda within working memory over a short delay period (e.g., 3 sec) and respond as to whether a working memory probe was or was not included in the current working memory set. Neuroimaging studies indicate that the frontal lobes, including the DLPFC, middle frontal gyrus, and IFG, are associated with Sternberg working memory processing (e.g., Zhang, Leung, & Johnson, 2003; Reuter-Lorenz et al., 2000), and frontal damage can impair performance on this task (Grön, 1998).

In some variations of the Sternberg item recognition test, participants must follow cues or directed forgetting instructions to correctly control the contents of their working memory (e.g., Festini & Reuter-Lorenz, 2013, 2014, 2017; Nee & Jonides, 2008; Nee et al., 2007; Oberauer, 2001, 2005). When these less relevant memoranda are presented as probe items, individuals have lengthened RTs and are more susceptible to false alarms (e.g., Festini & Reuter-Lorenz, 2013, 2017; Nee et al., 2007; Oberauer, 2001, 2005). Oberauer (2005) reported that younger adults with low working memory capacity committed more false alarms to intrusion probes, indicative of inefficient frontal control. Moreover, older adults also show more sizeable intrusion costs than younger adults (Oberauer, 2001). Neuroimaging evidence indicates that directed forgetting interference within working memory activates the left dorsolateral and bilateral VLPFC (Nee et al., 2007). Note that such neuroimaging findings often contrast high-interference conditions with low interference conditions, and additional neuroimaging analyses that examine neural activation during false alarms specifically would be beneficial.

**Attentional Tasks**

There is little argument that frontal regions play a key role in a variety of attentional processes; rather, as with other frontal processes, a key question has been the extent to which the frontal lobes act as “a general global capacity processor, or a series of fractionated processes” (Stuss, 2006, p. 261). On one task specifically designed to investigate the localization of attentional processes, the ROBBIA (Rotman–Baycrest Battery to Investigate Attention, named after sculptor Lucca della Robbia and developed following Stuss’ theoretical work on attention), participants with damage to the left lateral region of the prefrontal lobe were more likely to respond with false alarms specifically, whereas patients with damage to the right lateral region demonstrated more errors of all kinds (Stuss, 2006). The ROBBIA, which included simple RT, choice RT, and prepare RT variants of a basic RT paradigm is just one example of a task-based investigation that supports the fractionation of frontal attention mechanisms.
CPTs measure both attentional and, arguably, inhibitory processes. In the AX variant of the task, participants are presented with a series of letters and are asked to respond only when specifically shown the letter X following the letter A (Bekker, Kenemans, & Verbaten, 2004). In general, modern analyses of the CPT consider both errors of omission and errors of commission, as well as $d'$ (sensitivity) or other measures drawn from signal detection theory (Häger et al., 1998). Widely used in populations of children with ADHD, the CPT has revealed age-related differences in false alarm rates by age (young children demonstrated many more false alarms than older children), and severity of neonatal lesions has been found to be linked to a higher number of errors of commission specifically (Kanaka et al., 2008; Katz et al., 1996). Age-related differences in false alarm rates on the CPT have also been identified in adult populations, with older adults experiencing more errors of commission than younger ones across several variants of a CPT task (Mani, Bedwell, & Miller, 2005).

One possibility that has only occasionally been explored in the CPT is whether commission errors are due to false responses (potentially linked to inhibition) or delayed responses that show up on the next stimulus (which may be linked more generally to inattention; Halperin, Wolf, Greenblatt, & Young, 1991; Halperin et al., 1988). Careful task analyses of the CPT, including differentiating between different types of errors of commission, has significant value in elucidating links between inhibitory control and sustained attention more generally, particularly given that differences in false alarm rates on the CPT are observed across ADHD diagnosis status, age, and lesions alike (Riccio, Reynolds, Lowe, & Moore, 2002).

Notably, increased false alarm rates have been observed over time on the CPT as the task progresses. The extent of these performance decrements may themselves be linked to right frontal lobe lesions (Rueckert & Grafman, 1996); however, this is not always observed across lesion or head injury studies utilizing vigilance tasks (Parasuraman, Mutter, & Molloy, 1991). Given the utility of a carefully designed CPT as a measure of both impulsivity and sustained attention, further studies should examine how different outcome variables, including false alarm rates, may be associated with different underlying domains of function.

**Interference Control Tasks**

**Recent Probes**

The recent probes task introduces familiarity-based memorial interference within working memory (e.g., Irlbacher, Kraft, Kehrer, & Brandt, 2014; Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, 2003; Zhang et al., 2003; D’Esposito, Postle, Jonides, & Smith, 1999). While performing a working memory item recognition test, participants are occasionally shown a probe item that originated from the recent trial instead of the current trial. Such familiarity-based interference induces lengthened RTs and more false alarms (e.g., Festini & Reuter-Lorenz, 2014; Jonides & Nee, 2006; Badre & Wagner, 2005; Jonides et al., 2000).

Lesion studies demonstrate the importance of the left IFG in familiarity-based interference resolution. Thompson-Schill et al. (2002) report a case study, R. C., who had targeted damage to the left IFG. While performing the recent probes task, R. C. committed frequent false alarms to recent probes and had considerably lengthened RT interference effects—both of which were over 3 standard deviations above the control group’s interference effects—and also significantly exceeded the interference effects shown by patients with different frontal lesions. Age effects were also observed, such that older adults had greater interference-induced false alarms than younger adults (Thompson-Schill et al., 2002; Jonides et al., 2000), as well as reduced activation of the left IFG (Jonides et al., 2000). Given this evidence, the left IFG has been shown to be critical to help avoid false alarms in the face of familiarity-based interference.

**False Memory**

The term “false memory” often refers to a failure in memory when an individual recalls or recognizes something that is associatively similar to studied memoranda but was never encoded (e.g., Gallo, 2013; Roediger, Watson, McDermott, & Gallo, 2001). In studies of false memories, encoded memoranda are often manipulated to be semantically similar, making associative errors more likely. Hence, avoiding false alarms to associatively related lures requires interference control.

Greater incidence of false memories has been observed with frontal dysfunction. For instance, participants with executive impairment on the Trail Making Test had increased susceptibility to false memories (LaVoie, Willoughby, & Faulkner, 2006). Moreover, individuals with frontal damage demonstrated more false memories than control participants within the Deese–Roediger–McDermott (DRM) paradigm (Melo, Winocur, & Moscovitch, 1999; but see Warren, Jones, Duff, & Tranel, 2014). Individuals at risk for schizophrenia with early indications of psychosis also exhibited more false alarms on DRM tasks and reduced functional brain activation relative to controls, including in the left middle frontal gyrus and bilateral medial frontal gyri (Allen et al., 2011; but see Elvevag, Fisher, Weckert, Weinberger, & Goldberg, 2004).

Although aging has been associated with heightened false memories (e.g., Butler, McDaniel, Dornburg, Price, & Roediger, 2004; Balota et al., 1999; Norman & Schacter, 1997), age differences in false memories are not always found (e.g., Gutches & Park, 2009, for picture stimuli; LaVoie et al., 2006). Several studies implicate frontal dysfunction as a contributor to age effects. Butler et al. (2004) observed that only older adults with neuropsychological performance indicative of frontal impairment exhibited more false memories (see also Roediger & Geraci,
2007). A similar effect of frontal lobe function on false memories in older adults was replicated by Meade, Geraci, and Roediger (2012). Thus, the higher incidence of false memories in older adults can be partly attributed to frontal deficits.

**Inhibitory Control Tasks**

Inhibitory control and prepotent response inhibition refer to the process of suppressing or stopping an action when that response may be compelling but is inappropriate in a particular context. Studies with inhibitory control tasks often involve frontal lobe recruitment as well as a motor response element (Mostofsky & Simmonds, 2008). Given this, false alarms are a key outcome variable within inhibitory control tasks, including the go/no-go task (Donders, 1969) and stop-signal task (SST; Logan & Cowan, 1984). The SST is not considered in detail here because it does not necessarily induce a false alarm by our definition. Rather, the SST examines the ability to inhibit a motor program that has already been initiated, whereas other tasks that also benefit from efficient motor inhibition can involve false alarms in response to a stimulus, such as erroneously responding to a no-go stimulus.

The go/no-go task requires that participants respond to target go trials when no-go stimuli are interspersed, generally at a smaller percentage (often somewhere between 10% and 25% of trials). A variety of early lesion studies utilizing the go/no-go task found higher false alarm rates among individuals with frontal lobe damage (e.g., Drewe, 1975); furthermore, at least one study found that such errors were reduced following removal of a falx meningioma in the medial frontal region (Leimkuhler & Mesulam, 1985). Importantly, a more recent lesion study examining go/no-go task performance also found an increase in false alarm rates among individuals with lesions to the left IFG, as compared with individuals in a control group (Swick, Ashley, & Turken, 2008). Lesion work by Picton, Stuss, and colleagues similarly implicated the left frontal cortex in the production of false alarms during a go/no-go paradigm (Picton et al., 2007). Even more recently, Arbula et al. (2017) documented that left ventrolateral and left dorsolateral prefrontal lesions yielded higher false alarm rates to no-go stimuli as well as higher false alarms to warning cues on a simple RT task, whereas right prefrontal damage did not lead to such false alarms. Collectively, these studies suggest a role for the left frontal regions in inhibitory control, particularly inhibitory control that requires motor decisions, rather than pure inhibition of movement alone. Indeed, Aron, Robbins, and Poldrack (2014) explain that the right inferior frontal cortex is critical to the specific inhibition of prepotent responses (i.e., as with an SST), whereas go/no-go tasks can require a different form of inhibition that utilizes decisions and response selection based on task rules, for instance.

Developmental neuroimaging studies utilizing the go/no-go task have found (a) significantly higher activation within dorsal and lateral prefrontal cortices in children versus adults and (b) that activity in the orbital frontal and ACC was associated with false alarm rates (Casey et al., 1997). Lastly, converging data from studies examining alcohol usage effects on inhibitory control using the go/no-go task have also highlighted reduced activation in frontal regions associated with response inhibition and often greater false alarm rates, relative to control participants (Ahmadi et al., 2013; Finn, Justus, Mazas, & Steinmetz, 1999).

**Summary of Frontal Contributions to False Alarm Regulation**

From the aforementioned research, it is clear that there are significant frontal contributions to the regulation of false alarms. Lesion studies consistently demonstrate that frontal damage can lead to heightened false alarms on a wide variety of tasks, including recognition tests (e.g., Schacter et al., 1996), DRM paradigms (Melo et al., 1999), Sternberg working memory tasks (Grön, 1998), the ROBBIA (Stuss, 2006), recent probes tasks (Thompson-Schill et al., 2002), and go/no-go tasks (Drewe, 1975). Moreover, much behavioral and neuroimaging data concordantly indicate that individuals with less efficient frontal lobe processing often commit more false alarm errors. Such heightened false alarms with frontal inefficiency have been observed in older adults (e.g., Gajewski & Falkenstein, 2014; Mani et al., 2005; Oberauer, 2001; Jonides et al., 2000; Dywan & Jacoby, 1990), in children (e.g., Kanaka et al., 2008; Levin et al., 1991), and in individuals with ADHD (e.g., Riccio et al., 2002; Losier et al., 1996), schizophrenia (e.g., Allen et al., 2011), and alcohol dependence (e.g., Ahmadi et al., 2013; Finn et al., 1999), for instance.

As highlighted earlier, the fact that false alarms can be made on otherwise dissimilar tasks across multiple domains makes them a promising error type for understanding the potential unity or separability of frontal neural resources. Whereas certain tasks are thought to favor motor regulation (e.g., go/no-go), others focus on interference control (e.g., recent probes, DRM tasks), attention (e.g., ROBBIA), or memory performance (e.g., episodic long-term recognition, Sternberg working memory). See Table 2 for representative examples of false alarms and false-alarm-like errors, across different tasks, as well as example implicated neural correlates. To aid in the interpretation of neural data, we have included Figure 3, which depicts the general location of frontal subregions relevant to the commission of false alarms.

In aggregate, these summarized findings provide evidence for distinctions between discrete parcellations of the pFC, as proposed by Stuss and others. Generally, each of the regions discussed here may be involved in the regulation of false alarms within specific contexts, and we find reasonably strong evidence for frontal fractionation across task domains. For example, Arbula et al. (2017) find clear dissociations between left and right prefrontal damage, such that only individuals with left prefrontal lesions experience...
Table 2. Representative Examples of False Alarm Studies with Neural Data across a Variety of Test Domains

<table>
<thead>
<tr>
<th>Test Domain</th>
<th>Representative Example</th>
<th>Task Used</th>
<th>Design</th>
<th>Imaging or Lesion Localization Methodology</th>
<th>Neural Correlate Implicated</th>
<th>Key False Alarm Finding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Episodic long-term memory</td>
<td>Alexander et al. (2003)</td>
<td>California Verbal Learning Test</td>
<td>33 patients with frontal injury compared with 11 with nonfrontal lesions compared with 14 nondamaged controls</td>
<td>CT and MRI structural imaging to classify lesions</td>
<td>Left posterior DLPFC</td>
<td>False alarms highest for posterior left DLPFC damage group on recognition memory subtest</td>
</tr>
<tr>
<td>Working memory</td>
<td>Gajewski &amp; Falkenstein (2014)</td>
<td>n-Back</td>
<td>36 young compared with 36 older healthy individuals</td>
<td>ERP data collected during performance on 2-back and 0-back control task</td>
<td>P3a measured at Fz</td>
<td>Older adults exhibited more false alarms on 2-back task than younger adults; frontal P3a was reduced in older adults</td>
</tr>
<tr>
<td>Attention</td>
<td>Rueckert &amp; Grafman (1996)</td>
<td>Continuous performance test</td>
<td>11 patients with left frontal lesions, 10 patients with right frontal lesions, and 16 nonlesioned controls</td>
<td>Lesion localization through CT and/or MRI</td>
<td>Right frontal lobe</td>
<td>Patients with right frontal lesions made a greater number of false alarms versus controls</td>
</tr>
<tr>
<td>Interference control</td>
<td>Thompson-Schill et al. (2002)</td>
<td>Recent probes</td>
<td>7 patients (middle-aged and older adults) with lateral prefrontal cortex damage, including one with damage to anterior portions of left middle and IFG (R. C.), compared with three control groups</td>
<td>Lesion localization through CT or MRI</td>
<td>Left anterior IFG</td>
<td>R. C. (patient with damage to left anterior IFG) experienced far greater interference-related false alarms relative to both controls and other lesion patients</td>
</tr>
<tr>
<td>Inhibitory control</td>
<td>Arbula et al. (2017)</td>
<td>Go/no-go task</td>
<td>10 patients with left prefrontal lesions, 11 patients with right prefrontal lesions, and 16 patients with nonprefrontal lesions</td>
<td>Lesion localization through MRI</td>
<td>Left pFC</td>
<td>Patients with left pFC damage showed both higher omission errors and higher false alarm rates while patients with right pFC damage showed primary omission errors</td>
</tr>
</tbody>
</table>
highlighted false alarms on a go/no-go task. That being said, there are likely some shared processing resources, particularly those related to monitoring and goal maintenance mechanisms that have been linked to the DLPFC. For example, an individual who has more general difficulty maintaining task instructions may be more likely to commit false alarms on a variety of tasks. But the possibility of shared error origins does not preclude clear distinctions between other error sources and tasks.

Thus, we argue that the commission of false alarms across different domains can involve distinct processes that are localized and specific to individual neural regions, even though there may be some frontal regions that exhibit shared governance. Given the limited research that clearly investigates this issue, it remains important for future research to more fully elucidate the extent to which these processes are shared versus task specific.

**DISCUSSION**

In this review, we summarized evidence for frontal lobe contributions to the regulation of false alarms across a wide variety of neuropsychological and experimental tasks. Although it would be possible to write a lengthy review about each task domain separately, we sought to compile and analyze critical evidence pertaining to errors of commission, false alarms, and false positives across numerous tasks. Although false alarms have been inspected within individual task domains, they are rarely considered concurrently across disparate tasks, despite the possibility that these errors may involve, to some extent, overlapping processes. Donald Stuss took care to note that the types of executive processes the frontal lobes perform are nuanced, should not be generalized, and are localized to specific frontal subregions (e.g., Stuss, 2011; Stuss & Benson, 1984). Thus, we aimed to examine sources of overlap as well as distinctions between regions of the frontal lobes that mitigate false alarms and to identify areas for future research, while also acknowledging that false alarms are complex and can occur for a variety of possible reasons across a myriad of task domains.

We outlined 11 reasons why false alarms may occur on various tasks. To summarize, we propose that false alarms may occur due to (1) difficulty maintaining task goals, (2) failure of stimulus–response mapping, (3) response selection difficulty, (4) deficient sensory processing, (5) deficient prepotent response inhibition, (6) deficient interference resolution, (7) lapses in sustained attention, (8) poor strategic monitoring, (9) item-specific recollection or familiarity, (10) deficient postretrieval monitoring, and (11) poor metacognition. These reasons are not mutually exclusive, as multiple mechanisms may contribute to an error of commission, nor are they necessarily orthogonal. At the same time, some tasks may have fewer/different sources of false alarms (e.g., an inhibitory control task would not suffer from a memorial processing impairment).

Efficient frontal lobe functioning, broadly defined, is proposed to be crucial for avoiding false alarms because of these mechanisms, except for deficient sensory processing, which is a nonexecutive perceptual deficit. The diversity of mechanisms that may contribute to a single error type should not be surprising, given that Stuss and colleagues similarly acknowledged the wide variety of operations that the frontal lobes perform to help regulate behavior, writing, “A major role of the frontal lobe is to control response options through marshalling inhibitory processes, establishing response selection, or maintaining constant activation of the intended goal” (Stuss, Foden, et al., 2001, p. 772). Thus, a primary aim of this review was to consider how a close examination of a single type of error (i.e., false alarms), across multiple tasks and domains, might inform our understanding of prefrontal organization.

According to the Cascade Model (Koechlin & Summerfield, 2007), the lateral pFC is organized in an anterior–posterior fashion, where anterior regions provide control signals to more posterior regions, and ultimately, an action is selected. In a similar vein, D’Esposito and Badre (2012) posited that rostral (anterior) frontal regions perform more abstract control processes (e.g., maintenance of higher level rules), whereas caudal (posterior) frontal regions perform more specific control of movements (see also Bahlmann, Blumenfeld, & D’Esposito, 2015). They suggest a hierarchical organization, such that posterior frontal regions receive input from anterior regions (D’Esposito & Badre, 2012). Although, newer evidence suggests that multiple global and local frontal hierarchies may be involved, that more caudal regions like the anterior mid-DLPFC may also assist with abstract processing, and that communication between the frontal cortex, striatum, and thalamus may also be critical for regulatory control over behavior (Badre & Nee, 2018). In line with these models, we propose that, depending on the individual nature of the task and the situational context, an error in processing may occur in any of the anterior or posterior regions (i.e., at any place in the cascade or hierarchy) that could ultimately result in a false alarm. Multiple processing errors may also occur across several regions in the hierarchy. Thus, the pFC maintains higher level rules that help direct cognitive processing within and beyond the frontal lobe, influencing the commission of false alarm errors.

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**Figure 3.** Diagram of the approximate anatomical locations of prefrontal subregion relevant to false alarms. Dotted lines denote overlaid medial view. Modified from the brain images courtesy of Assoc. Prof. Frank Gaillard, Radiopaedia.org, rID: 46670, rID: 47208.
In other models, frontoparietal networks have been proposed to be domain-general, contributing to performance across disparate challenging tasks that require executive functioning (e.g., Fedorenko, Duncan, & Kanwisher, 2013; Niendam et al., 2012). Using single-subject analysis, Fedorenko et al. (2013) demonstrated that the same voxels were activated across different types of executive tasks (e.g., spatial and verbal working memory forced-choice recognition tests). Specifically, this multiple-demand system consists of a network of brain regions, including the inferior frontal sulcus, dorsal ACC, pre-SMA, insula, and intraparietal sulcus, and is posited to be utilized across many different complex tasks (see Duncan, 2010). Similarly, Niendam et al. (2012) provide evidence in support of a superordinate cognitive control network encompassing frontal, cingulate, and parietal regions. Their meta-analysis documented similar activation patterns across a variety of executive tasks, including tasks that can elicit false alarms, like the go/no-go, n-back, and Sternberg working memory tasks. Importantly, in both models, the existence of domain-specific frontal regions is also supported (Fedorenko et al., 2013; Niendam et al., 2012). As such, false alarms within a variety of tasks may result because of failure of either domain-general or domain-specific frontal areas, depending on task parameters, context, and individual differences across participants.

Finally, consistent with the notion of domain generality, the unity and diversity framework (Friedman & Miyake, 2017) asserts that executive function subtypes (e.g., prepotent response inhibition, working memory updating) show both shared and dissociable aspects. The authors note, however, that there is little consensus as to the neural correlates of specific executive functions, as well as if individual differences in executive function abilities will map onto the same brain regions that are activated at the group level (Friedman & Miyake, 2017). Indeed, activation of a particular frontal region during an executive task may be indicative of task monitoring, inhibition, or multiple processes (see Friedman & Miyake, 2017), and inefficiencies in different types of executive functions (e.g., inhibiting, shifting) may be responsible for false alarms, making it difficult to ascribe specific frontal subregions to false alarm regulation on specific tasks.

Summary of False Alarm Links to Neurophysiology: Unity Versus Separability?

Clearly, one of the core takeaways of this article is that additional neurophysiological research—that specifically considers the commission of false alarms across different tasks within both fMRI and lesion studies—is essential for understanding how the specific mechanisms of performance on these tasks might provide support for differing theoretical perspectives of frontal lobe functioning. Drawing strong conclusions from extant literature is further challenged by the fact that not all lesion work provides specificity about the location of damage and that this may or may not line up with common ROI coordinates used in fMRI work. Thus, it is premature to draw overly strong conclusions about whether extant work provides support for a more unified or diverse view of prefrontal function. That being said, we believe that the literature reviewed here provides at least preliminary evidence for some parcellation of prefrontal performance across disparate tasks. For example, we see that the left pFC (including left ventrolateral and left dorsolateral cortex) is implicated in false alarms because of decisional impairments, whereas the right pFC (particularly right ventrolateral) is implicated in sustained attention deficits (Arbula et al., 2017). Were dissociations like this not to exist, it might provide more evidence for a unified framework of prefrontal function. Given that there are instances where particular neural mechanisms are implicated in the commission of false alarms on some tasks and not others, Stuss’ perspective on prefrontal fractionation remains a relevant and compelling view.

Support for Stuss’ Account of Frontal Functioning

Throughout his extensive career, Donald Stuss argued that there is not a single overarching executive process and that it is overly simplistic to equate frontal damage broadly and nonspecifically to executive deficits (e.g., Stuss, 2011; Stuss & Alexander, 2007; Stuss, Shallice, Alexander, & Picton, 1995). Instead, he was a key proponent of frontal lobe parcellation and careful task analysis to determine localization of cognitive processes, including a focus on error analyses and feedback, finding that, in one well-cited example, “if error analysis can be considered an indirect reflection of control mechanisms, this study demonstrates different disorders of control related to lesion location within the frontal lobes” (Stuss et al., 2003, p. 2376). Stuss, along with his colleagues, went as far to design a task battery, the ROBBIA, that allowed them to specifically investigate the fractionation of frontal control processes (see Stuss, 2006).

The findings from this review support this perspective and, furthermore, highlight the utility of this approach in considering a shared error type (false alarms) across a variety of wide different cognitive tasks. Stuss himself noted that similar monitoring deficits, for example, may affect performance on very different tasks (Stuss, 2011). Although there is not yet a substantial body of experimental or computational work that incorporates this approach at the expansive level conducted in this review, we believe that it may prove particularly valuable for further defining the underlying mechanisms and neural correlates of false alarms across a variety of executive function tasks.

Directions for Future Research

In some tasks, the false alarm is a primary dependent measure, as in the go/no-go task or in DRM paradigms. In other
tasks, although false alarms or errors of commission may disrupt performance, they are not always specifically assessed. The \( n \)-back task, for instance, is widely used as a measure of working memory, and formal analysis of false alarms to lure trials is infrequently reported. Similarly, in memory recognition tasks, false alarms are not always considered in detail, as a larger focus tends to be on accuracy scores or measures like \( d' \) or \( A' \) that consider hits and false alarms simultaneously. Although there is extensive support for the importance of reporting and analyzing signal detection measures like \( d' \), we argue that supplemental reports of false alarms for these tasks would also be beneficial to more fully characterize the data and allow for detailed comparisons between tasks. At a minimum, the findings of this review support the utility of examining false alarm variables specifically, even when composite variables like \( d' \) are also useful—each gives important information that serves to expand knowledge of core cognitive processes.

Obviously, false alarms should not be examined in isolation, however. Reporting both hit rates and false alarm rates, considering one in the context of the other, for instance, is beneficial for a more complete depiction of performance. Normal hit rates and high false alarm rates may be more indicative of frontal deficits, where false alarms may result from poor monitoring of memory (e.g., Verfaellie et al., 2004), whereas low hit rates and high false alarm rates may be more indicative of poor memory, because of hippocampal or medial-temporal lobe lesions, for example (Eichenbaum et al., 2010; Verfaellie et al., 2004). Similarly, errors of omission are also informative, as, for instance, they may indicate worse attentional vigilance and, paired with high false alarms, may be informative of attention deficits.

Another direction for future research would be to conduct within-subject analyses of false alarms across a diverse range of tasks. Currently, false alarm analyses are often restricted to cognitive processing domains within separate specialties, such as response inhibition analysis, false memory analysis, or working memory analysis. To better distinguish which possible sources of false alarms are contributing to poor performance, individuals with specific frontal lobe lesions could perform a wide array of tasks and predictions could be made as to on which tasks false alarms would be most prevalent given the location and extent of the frontal damage. For instance, if poor strategic encoding was hypothesized to be the primary deficit of the individual, one could predict heightened false alarms on tasks that require strategic encoding (e.g., DRM paradigms, episodic memory tasks) but fewer false alarms on tasks like the go/no-go task because strategic encoding is not a contributor toward false alarms on that task. In our review of the literature, while there are occasional extensive assessments of case studies across multiple tasks (see Arbula et al., 2017, for an important examination of false alarms on go/no-go and simple RT tasks), we believe the field would benefit from more deliberate within-subject analysis of false alarms across a range of cognitive tasks.

Moreover, even in neurologically intact individuals with no evidence of brain damage, individual differences in susceptibility to false alarms are evident. Healthy individuals could perform a large variety of tasks within the laboratory, with careful analysis of consistencies and inconsistencies between false alarms across tasks. Neuroimaging analyses could also help identify sources of neural overlap in the resistance to or commission of false alarms across tasks. Such detailed within-subject analysis of false alarms across tasks would help identify which sources of false alarms (e.g., lapses in sustained attention, deficient interference resolution) are most common for which tasks and would further Stuss’ goal to carefully ascribe specific executive processing abilities to particular regions of the frontal lobe.

Optimally, this would also be done in conjunction with fMRI studies on both typically developing individuals as well as patients with frontal lesions. Patterns of brain activity that are evident in those with frontal damage are informative of the potentially spared executive operations, albeit with consideration of reorganization and neuroplasticity as the result of the brain damage. Additionally, computational modeling may serve as a useful complementary methodology for studying false alarms across a wide variety of cognitive measures. Given the surfeit of tasks and domains in which false alarms may exist and the potential complexity surrounding their commission, computational modeling will likely help inform both future theoretical and experimental research.

Future research should also place greater emphasis on deliberate fractionation and localization work to tease apart which cognitive processes are associated with distinct subregions within the frontal lobe. Neuroimaging studies have been more consistent in their description of precise frontal activations, but lesion studies often refer to general, nonanatomically specific frontal damage, although some more recent human lesion work is anatomically specific (e.g., Thompson-Schill et al., 2002). When possible, more specificity regarding the exact location of the damage would help distinguish the roles of different frontal subregions.

Conclusion

Following Stuss’ call to consider distinct processes across individual regions of the frontal lobes, we evaluated false alarm errors across a wide variety of tasks. To our knowledge, this is the first time this has been done in a single article. We established that the frontal lobes are associated with the regulation of false alarms across episodic long-term memory, working memory, interference control, attention, and inhibitory control tasks. In particular, the frontal regions that have been consistently implicated in false alarm regulation across task domains include the DLPFC, VLPFC, APFC, ACC, and IFG. However, not all types of frontal lobe dysfunction necessarily result in elevated false alarms, with some variability among individuals and dysfunction location. Although extant work is limited, there is some evidence for the separability of frontal...
contributions to these errors. For instance, a dissociation appears to exist between the function of the left versus right prefrontal cortices, such that left prefrontal areas are more implicated in false alarms following deficient response selection (Arbula et al., 2017; Stuss, 2006). Future research targeted toward the assessment of false alarms specifically will be critical for confirming this finding and for identifying similar parcellations of frontal subregions associated with different sources of false alarms, such as the 11 sources we identified. Specifically, we propose that future within-subject studies of false alarms that utilize human neuroimaging, lesion studies, and computational modeling, across several tasks from multiple cognitive domains, will be critical for the detailed understanding of when false alarms are most likely to occur and, furthermore, for determining the extent to which making these errors involves shared or disparate processes. Such work has the potential to more fully characterize the frontal lobes’ regulation of false alarms and to inform therapeutic interventions for individuals with frontal lobe damage, as well as other frontal inefficiencies.

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Reprint requests should be sent to Sara B. Festini, University of Tampa, 401 W. Kennedy Blvd. Tampa, FL 33606, or via e-mail: sfestini@ut.edu.

Author Contributions

Sara Festini: Conceptualization; Funding acquisition; Investigation; Visualization; Writing—Original draft; Writing—Review & editing. Benjamin Katz: Conceptualization; Investigation; Visualization; Writing—Original draft; Writing—Review & editing.

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Diversity in Citation Practices

A retrospective analysis of the citations in every article published in this journal from 2010 to 2020 has revealed a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first-author/last-author) publishing in JoCN during this time period were M(an)/M = .408, W(oman)/M = .335, M/W = .108, W/W = .149; the comparable proportions for the articles that these authorship teams cited were M/M = .579, W/M = .243, M/W = .102, W/W = .076 (Pulvino et al., JoCN, 33:1, pp. 3–7). Consequently, JoCN encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article’s gender citation balance. The authors of this article report its proportions of citations by gender category to be as follows: M/M = 0.547, W/M = 0.208, M/W = 0.123, and W/W = 0.123.

Note

1. We note that errors of commission and failure to inhibit responses are often used to describe errors from other tasks, such as the stop-signal task, that do not necessarily involve an incorrect affirmation of a given signal.

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