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REVIEW

From Cognitive Neuroscience to Geriatric Neuropsychology: What Do Current Conceptualizations of the Action Error Handling Process Mean for Older Adults?

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Abstract The fields of cognitive neuroscience and neuropsychology have contributed an extensive corpus of research to the study of error monitoring processes in younger adults; however, less is known about error handling in older adults. This paper highlights current conceptualizations of error detection and correction in healthy and impaired older adult populations. The literature suggests that some error handling processes require fewer processing resources than others and may be performed relatively automatically. Compared with young adults, older adults demonstrate a reduced ability to recognize errors, but exhibit similar rates of correction. Older adults diagnosed with a neurodegenerative disease (e.g. Alzheimer's disease) show a reduced ability to detect and correct their action errors. Thus, neurodegenerative disease processes amplify the impairments in error identification associated with normal aging by disrupting both automatic and controlled error corrections. The clinical implications of our current knowledge are discussed, and directions for future neuropsychological research are offered.

Keywords Error detection · Error correction · Performance monitoring · Aging · Older adults

Introduction

The production of erroneous behavior is a costly facet of everyday human activity (Sarter & Alexander, 2000; Blavier et al. 2005) Although some errors of action may simply result in personal agitation and inconvenience, others may give rise to irreversible consequences that jeopardize individual safety (Rabbit 1978; Reason 1990). The arguably unavoidable nature of human error has resulted in a gradual change of focus in the performance monitoring and everyday action literatures. While previous studies directed their attention primarily to "error prevention" aids (e.g. minimizing the incidences of errors; Reason 2000), recent research underscores the importance of sophisticated error monitoring behavior and compensatory management strategies (Blavier et al. 2005; Dehaene et al. 1994; Reason 2000). Since errors of action may never prove to be wholly unavoidable, the ability to accurately and quickly detect one's blunder may be a more tenable goal.

Rapid error detection and correction remains particularly salient for older adults, as the inability to recognize and correct behaviors that deviate from established task parameters may impact an individual's ability to live alone and function autonomously. For example, a pressing functional issue for older adults centers on their capacity to drive an automobile. A recent review by Anstey and colleagues suggests that the *ability* to drive necessitates a host of cognitive, sensory, and motor functions; however, they concluded that ability to drive *safely* required intact monitoring of behavior (Anstey et al. 2005). While driving remains an important, albeit highly complex ability to appraise, action monitoring and error handling are also important issues to consider when evaluating activities of daily living (ADL's). ADL's include the capacity to maintain appropriate eating and grooming habits, and may involve utilizing devices such as a stove or an electric iron. Instrumental ADL is the term to denote more complex ADL that require numerous objects and steps that unfold over an extended period of time (e.g., laundry, medication manage-

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ment, etc.). Although many ADL and IADL are highly familiar and routine, they require complex on-line processing of actions, environmental cues, and outcome in order to safely complete the task steps and goals (Norman 1981; Schwartz 2006). Failure to turn off a stove, oven, or electric iron in a timely fashion may imperil an individual's safety and at the extreme, their life. Recent studies show that neurologically impaired individuals, including older individuals diagnosed with a dementia, frequently show deficits in both basic and instrumental ADL (Buxbaum 2001; Giovannetti et al. 2002a); thus, the ability to detect one's error, determine the source of the problem, and correct the blunder represents an important facet of functional autonomy that is specifically germane to geriatric populations.

In this paper we use the term "action errors" to refer to blunders in goal-directed behavior, *excluding* low-level motor acts (e.g. errors in motor precision) and language tasks (e.g. naming). Although on-line monitoring of action errors has been well researched in the fields of cognitive psychology and cognitive neuroscience, this issue has remained relatively neglected by the more applied fields, such as geriatric neuropsychology. As such, the current article focuses on three primary aims: 1.) to address current conceptualizations of action error handling in young adults, 2.) to provide an extensive review of recent empirical work on action error handling in geriatric populations, and 3.) to establish future directions for clinical research on error handling in older adults. While the error handling process shares similar characteristics with more general awareness deficits associated with classic neurologic syndromes (e.g., hemispatial neglect, Anton's syndrome, etc.), this paper does not aim to explicate the superordinate construct of "awareness." Furthermore, although important performance monitoring literature exists within the fields of human factors and linguistics, only articles that specifically impart cognitive or neuropsychological perspectives on *action* error detection and correction will be included in the following review.

Action Error Processes

Before commencing a discussion of the action error handling process, it is important to provide more information on the definitions of "errors." Previous work on action monitoring suggests that errors of action may reflect the "non-attainment of a goal" (Norman 1981; Reason 1990; Zapf et al. 1992; Zapf & Reason 1994) or a "deviation from the norm" based on either internal or external codes of accuracy. Numerous error taxonomies have been proposed in order to elucidate the derivation and impact of errors (Senders & Moray 1991). Within the domain of cognitive psychology, Reason (1990) established one of the more influential error classification systems (see also Norman 1981). He suggested that errors be classified according to a simple taxonomy of three cognitive stages, namely planning, storage of information, and execution of action. The first cognitive stage encapsulates the formation of one's intention and planning of the subsequent action. An error produced in this domain results in a "mistake," which refers to an incorrect intention. The intention is considered incorrect because it is atypical or inappropriate for the task context. Although the intention is wrong, the action plan is correctly executed according to that goal. The second stage involves the storage and retention of task-salient information. An error within this processing stage results in a "lapse," which suggests a deficit in retaining information appropriate for the task parameters. This may include an inability to retrieve the formulated intention at a specified time or indefinitely. The final stage consists of executing the specified action. Reason (1990) refers to an error produced in this last domain as a "slip," which refers to the incorrect implementation of a correctly formulated intention and plan. Although other classification systems have been proposed (See Blavier et al. 2005 for an extensive review; Zapf & Reason 1994), Reason's error taxonomy (1990) highlights the importance of the internal, cognitive aspects of error production, thereby offering a means of understanding the individual's personal role in on-line error detection.

Part 1

To Err is Human…To Monitor Divine: What We Have Learned from Young Adults

Cognitive Psychology: Early Studies of Error Monitoring

The empirical analysis of error detection and correction dates back more than 50 years, with early studies documenting slowed responding immediately after the commission of an error (Rabbitt 1969). This behavior, referred to as "post-error slowing," has been observed even in studies where participants were explicitly instructed not to correct or to ignore their errors (Rabbitt 1968). Furthermore, studies have shown that young adults correct their errors in reaction time tasks frequently (75–85% of the time, Rabbitt 1968), rapidly (Rabbitt 1966a, b), and, in some cases, without conscious awareness (e.g. reporting no subsequent awareness of committing an error). These early studies in the 60's and 70's suggested that error processing is multidimensional and that some components of the error handling process may be performed in a highly automatized manner.

Arising from these conclusions, numerous theories have since been proposed to encapsulate the cognitive and neuropsychological processes associated with the behaviors that occur after an error is committed. These behaviors are commonly referred to as "action error handling." Although the error handling phase has been primarily subdivided into two stages (Zapf & Reason 1994; Reason 1990), an appraisal of the cumulative evidence suggests that there may be three distinct phases: detection, explanation/identification, and correction (Blavier et al. 2005; Sellen 1994; Sellen & Norman 1992). The vast majority of cognitive research merges the first two phases, thereby referring to "detection" in the most general sense of identifying and explaining the error.

The mismatch theory of detection represents one of the first comprehensive accounts of how an individual becomes aware of an action blunder (Reason 1990). According to this account, error detection occurs as a result of mismatch between outcome and intention (Reason 1990; Rizzo et al. 1995). This is very similar to closed-loop theories of motor learning, in which individuals detect errors by comparing proprioceptive feedback from the environment with internal representations of the goal (Adams 1971; Colley 1989; Schmidt 1975). Mismatch explanations of error detection are particularly sensitive to the role of "intention" in error behavior, as the intention of the actor renders different predictions for the likelihood of certain types of errors being detected. For example, if an individual develops an incorrect action plan and then proceeds to carry out the task (e.g. a "mistake" according to Reason 1990), they are unlikely to detect an error because their actions are based on faulty intentions (see also Sellen & Norman 1992). Reason's as well as Sellen & Norman's taxonomies of *detection* emphasize cognitive processes associated with error monitoring, and thus offer a means for predicting which errors are more likely to be detected under various contexts. For example, slips are more often detected through action-based mechanisms (Sellen & Norman 1992), as the individual has developed an appropriate intention, but simply failed to carry it out correctly; thus, they remain privy to internal and external feedback throughout the execution of the action (Norman 1981). Mistakes, on the other hand, are more likely to be detected through outcomes, namely due to the fact that mistakes are not in conflict with internal plans and thus rely only on external feedback. The distinct detection mechanisms for slips and mistakes are depicted in Fig. 1.

The next two phases of error handling, identification and correction, remain the least studied facets of error monitoring. Error identification refers to understanding the nature of the error that has occurred; thus, above and beyond noticing a problem in the environment, an individual localizes the error and understands why it is rendering negative effects. Empirical studies of problem solving suggest a dissociation between error detection and error identification. For example, in a study by Allwood (1984), young adults were required to "talk through" their problem solving techniques to produce a correct answer on a statistical task. Allwood's results showed that individuals often detected that a problem has occurred, but participants were not always capable of fully explaining or localizing the error. In general, error correction did not occur in cases where the error was not adequately identified.

Finally, the last stage of the 'error handling process' is error correction. Error correction consists of rectifying a problem or, if consequences are irreversible, suppressing the error's negative effects (Sellen 1990; Ohlsson 1996). Despite limited cognitive research on this topic, researchers have offered several suggestions regarding the viability of and time frames associated with error correction. First, mistakes require an arduous process of detection due to the lack of internal or action mismatch (see Fig. 1). As a result, mistakes frequently necessitate intervention from an external source, prolonging and at times obviating the correction process (Blavier et al. 2005). Second, overt slips are thought to be easier to detect, and thus are more likely to be corrected promptly. Third, as mentioned previously,

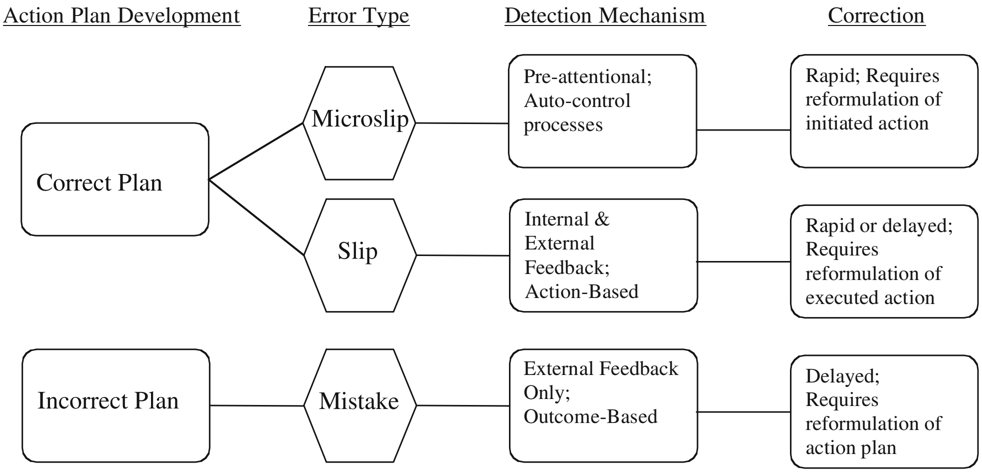

Fig. 1 Differential monitoring mechanisms for microslips, slips and mistakes

research suggests that some corrections may occur even before the error is completely executed, which may reflect a more adaptive, less conscious, and less effortful monitoring system (e.g. microslips; Smid et al 1990). Corrective responses have been reported in the absence of explicit detection of errors (i.e. when queried about corrective responses, participants do not report even being aware of producing the error) and have been documented as occurring prior to or after detection (Rabbitt 1966a).

Cognitive Neuroscience: Electrophysiology, fMRI, and Computational Modeling

Although early cognitive studies have provided a foundation for our understanding of behavioral error handling indices in healthy adults, methodological limitations prevent a comprehensive understanding of error detection and correction. Namely, parsing out the relative contribution of error *detection* to the action monitoring process remains a difficult task in cognitive studies. As such, neuroscience research has been pivotal in isolating the individual roles of error detection and error correction in performance monitoring. The fields of neurophysiology and cognitive neuroscience have contributed an extensive corpus of empirical research to the study of error monitoring processes, and thus have been able to offer insight into the neurophysiological and neuroanatomical structures most relevant to error handling. In order to garner a comprehensive understanding of the mechanism(s) by which people detect and correct their action errors, it is important to provide a brief overview of the findings ascertained from neuroscience research.

Fueled by methodological advances and increased interest in error processing, the early 1990’s witnessed a marked shift in our understanding of how the brain monitors, evaluates, and responds to errors. Utilizing event-related potentials (ERP), two independent laboratories (Falkenstein et al. 1991; Gehring et al. 1993) separately identified an ERP signal that reliably occurred at the onset of overt error responses. This signal was consistently characterized by a negative deflection in the ERP and was labeled “negativity associated with errors” (Ne; Falkenstein et al. 1991) or “error-related negativity” (ERN; Gehring et al. 1993). Hereafter, we will use the term “ERN” to refer to this response. The ERN peaks at approximately 80–100 ms after the initiation of an erroneous response and is maximal at frontocentral midline scalp sites (Gehring et al 1993; Kopp et al. 1996; Kopp & Rist 1999). The ERN has been observed following error production irrespective of stimulus presentation (Falkenstein et al. 2000) or response modality (Holroyd et al. 1998). Recent evidence confirming the ERN’s sensitivity to error processing includes the following findings: An ERN is produced when an individual knows the correct response but does not follow through with an appropriate execution (i.e. a *slip*; Dehaene et al. 1994), when an individual produces a late response in a deadline speeded response-task (Luu et al. 2000a), and when an individual receives feedback on recently committed errors (Miltner et al. 1997; Luu et al. 2000b). Recent findings suggest that ERN amplitudes are greatest when participants are actively engaged in error monitoring processes. However, there are several studies also showing evidence for the ERN even when participants are unaware of error monitoring behaviors (i.e. pre-attentional). The presence of the ERN without accompanying awareness of the error remains a controversial topic that will be discussed later in the review.

Notably, some studies have demonstrated a correlation between the ERN and subsequent error corrections (Gehring et al. 1993); however, more recent studies posit that the ERN is dissociable from the neurophysiological processes associated with error correction (Falkenstein et al. 1995; Scheffers et al. 1996; Falkenstein et al. 2000).

A second error-related ERP response, referred to as error positivity (Pe; Falkenstein et al. 1991), has been identified in relation to error correction processes. This positive wave has a centro-parietal distribution and occurs after the ERN, approximately 300 to 500 ms after an erroneous response has been made. Recent studies have implicated the Pe in the conscious processing or awareness of errors, thus differentiating it from the pre-attentional processing of errors that may be reflected by the ERN (Nieuwenhuis et al. 2001). However, like the ERN, the Pe is observed following slips rather than mistakes; thus if an individual’s intention is inaccurate (i.e., he/she does not know what the correct behavior is or erroneously believes his/her behavior is consistent with task parameters, as in a mistake), then Pe is not evident (Dehaene et al. 1994). More recently, Falkenstein and colleagues proposed three primary functions of the Pe, including conscious error recognition, affective error processing, and performance adjustments after an error (Falkenstein et al. 2005). The functional significance of the Pe *versus* the ERN remains a controversial topic; however, the two indices do appear to reflect different aspects of error processing.

Although ERP studies offer insight into the temporal dynamics of error processing and handling, they are limited in their ability to speak to neuroanatomical substrates associated with these processes. Functional imaging fills this gap by offering an important methodological tool for isolating brain regions associated with error processing. Within the last 15 years, the anterior cingulate cortex (ACC; Carter et al. 1998) has been strongly implicated in error processing. Despite the general agreement that error commission engages the ACC, much debate remains surrounding the specific role of the ACC in performance monitoring as well as the importance of other brain regions. ACC activations have been documented in response to errors as well as correct responses to items that evoke high response conflict. Thus, heated debate has ensued as to whether ACC activation reflects a general response to high conflict situations (regardless of whether the response is correct or incorrect) or is *specific* to error monitoring (Kiehl et al. 2000; Braver et al. 2001; Menon et al. 2001; van Veen & Carter 2002; Weissman et al. 2005; Weissman et al. 2003). Regardless, there is a general consensus that ACC activation is observed during conditions when error monitoring is likely to occur.

Recent attempts to unify ERP and fMRI data have resulted in two distinct models of error processing. The first account was put forth by Carter and colleagues (1998) and further refined by Botvinick and colleagues (Botvinick et al. 2001), and is referred to as the conflict hypothesis (for an extensive review, see Botvinick et al. 2004). This hypothesis suggests that the ACC monitors for the existence of conflict between simultaneously active but incompatible responses or action plans (Carter et al. 1998; Botvinick et al. 1999; Cohen et al. 2000; Botvinick et al. 2001; Weissman et al.. 2003). Thus, during errors, conflict occurs between the executed error response and activation of the correct response (van Veen & Carter 2002). The second model proposed to account for the ERP and fMRI data is a computational model developed by Holroyd and Coles, and is referred to as the reinforcement learning theory. According to reinforcement learning theory, responses are monitored by an “adaptive critic” in the basal ganglia that serves to evaluate whether events are better (positively valenced) or worse (negatively valenced) than expected (Holroyd & Coles 2002). This determination is subsequently signaled by an increase or decrease in dopaminergic activity, which influences the activation of the ACC. Thus, on this account, when an individual commits an error, inhibitory influences of the dopaminergic pathways are disturbed, which subsequently disinhibits neurons in the ACC and generates an ERN. Ultimately this serves to “fine-tune” the ACC and improve monitoring of future responses (Holroyd & Coles 2002; see also Aron et al. 2004; Holroyd et al. 2003; Yasuda et al. 2004; for alternative accounts concerning the role of the ACC in goal directed action see Weissman et al., 2005; Weissman 2006).

In terms of correction, very little neuroimaging research has been conducted on this topic, although it has been suggested that error detection and error correction are dissociable processes (Mathalon, Whitfield, & Ford 2003). Recent studies have hypothesized that the Pe response reflects a chain of responses beginning in the parietal cortex that ultimately activate the DLPFC to increase control over behavior and execute compensatory responses, although controversy persists surrounding this topic (Nieuwenhuis et al. 2001; Overbeek et al. 2005).

Another important issue that remains controversial is the role of conscious awareness in error processing. In a recent study by Scheffers and Cole (2000), participants were required to rate the accuracy of their responses (using a joystick) on an Eriksen flanker task, labeling their response as “Sure Correct,” “Unsure Correct,” “Don”t Know,” “Sure Incorrect,” and “Unsure Incorrect.” Overall, participants demonstrated compatibility between perceived accuracy and behavioral accuracy as defined by the RT response; however, perceived accuracy also covaried with the magnitude of the ERN amplitude. Thus, regardless of behavioral accuracy, the magnitude of the ERN was greatest for trials judged as “sure incorrect,” intermediate for trials judged as “unsure,” and small for trials judged as “sure correct.” Other studies have suggested that the ERN occurs after all errors, regardless of awareness, and instead it is the Pe that represents a delayed appraisal of the error (Nieuwenhuis et al 2001).

In sum, controversies still remain as to the specificity of the link between the ERN and error detection, the processes and neural substrates related to error correction, and the role of conscious awareness in error monitoring. However, the field of cognitive neuroscience has contributed tremendously to our understanding of the error handling process. Consistent with the behavioral research and cognitive models, these studies have corroborated the notion that error correction and error detection are dissociable and that error detection is not a unitary construct, but may be broken down further into pre-attentional and appraisal stages.

Part 2

The Effects of Healthy and Pathological Aging on Error Handling: What We Know and Don’t Know About Older Adults

The aim of Part 1 of this paper was to offer a brief introduction on action error handling in adults from a cognitive and neuroscience perspective. Behavioral studies, as well as neurophysiological and neuroimaging studies were reviewed to provide a foundation of knowledge of terms, methods, and concepts. The remainder of the paper will focus on how this knowledge of error monitoring processes has been applied to older adult populations.

Much less is known about action error handling in older adult populations. Given its relevance to activities of daily living and overall functional autonomy, it is important to highlight current conceptualizations of error detection and correction in older adult populations as well as identify future directions for research. The methodology employed in the following review entailed a PsychInfo and PubMed search using combinations of the terms “older adult,” “aging” (and age-related neurological diseases, e.g. “Parkinson’s disease”), along with the keywords “performance monitoring," "error detection," and "error correction." The initial search was limited to keywords, abstract, and title of articles. In order to isolate studies that specifically focused on action error *handling* as opposed to general error production / prevention (see Ridderinkhof et al. 2002; Pietrzak et al. 2007), inclusion criteria consisted of studies that included either error detection or correction as dependent variables. In addition, the review focused on on-line monitoring of action errors; thus, studies that primarily aimed to elucidate source-monitoring deficits[1] in older adults were not included (see Dywan et al. 2002). Finally, the meaning of the phrase "older adult" varies depending on the source of information examined. For the purpose of offering a comprehensive review, studies that utilize 50 or above as the *lower* age cutoff were incorporated into the review. After employing the prior criteria, 15 empirical articles on geriatric action error handling were selected for the current review. Publication dates ranged from 1979 to 2008.

The 15 studies selected for this review utilized a wide variety of tasks to evaluate error handling. In order to keep the review focused on conceptual issues, details of the methods used for each study were kept to a minimum in the text. More information regarding tasks used in the geriatric action error handling literature is provided in Appendix B.

Error Handling and Healthy Older Adults: Cognitive Studies

The first cognitive study to empirically examine how healthy older adults respond to action errors was conducted by Rabbitt (1979) using serial self-paced choice response task experiments. (See Table 1 for an overview of healthy older adult studies.) In terms of error detection and correction, young and older adults performed comparably well on these tasks, with both age groups detecting and correcting the majority of errors committed. Rabbitt conducted an additional study (1990) using a similar methodology as the 1979 study to elucidate the role of automaticity and interference in error detection and correction. Eighty participants from four age cohorts (see Table 1) were administered 600 successive trials on a two-choice serial self-pace choice response task. Participants were assigned to one of three groups and were given explicit directions on how to handle an error based on their group assignment. The "ignore" group was instructed to proceed through the task "as if nothing had happened," the "error correction" group was requested to immediately correct all errors they produced, and the "error signaling" group was instructed to press a panic button when they committed an error. Error production, as well as post-error slowing rates, did not differ among age cohorts or conditions, suggesting that older adults performed equally well on the tasks and demonstrated basic (i.e. low-level) recognition of errors. Supporting previous findings (Rabbitt 1979), this study also reported no difference in correction rates between age groups, suggesting that older adults can accurately rectify their behavior in an efficient manner; however, contrary to previous findings, older adults exhibited a decrement in error signaling relative to young adult participants. More specifically, individuals above the age of 50 signaled significantly fewer errors than young adults, and participants over the age of 70 demonstrated the fewest error signals of any age group. Finally, all participants were asks to retrospectively estimate the number of errors they produced in the experiment; regardless of the experimental condition, all participants underestimated their errors. However, the 70+ age cohort self-reported significantly fewer errors than the youngest cohort (18–29 year olds). The two early studies by Rabbitt offered preliminary information about the error handling processes in older adults and suggested that the aging process does not detrimentally impact basic error recognition (as evidenced by post-error slowing) or correction. The lack of overt error acknowledgement (e.g. signaling) may not initially appear problematic for older adult populations, as individuals are rarely asked to provide responses to errors without subsequently correcting them; however, decreased error signaling combined with the diminished retrospective recall of errors suggests that older adults may exhibit a reduced ability to consciously evaluate errors. This is consistent with neurophysiological studies of younger adults, which highlight an important distinction between low-level registration of an error and conscious evaluation of an error (Nieuwenhuis et al. 2001).

In a more recent cognitive study (2002), Rabbitt conducted a methodolologically similar choice recall experiment in which he varied the response-signal interval durations- the period between making a response and having to determine whether or not it was accurate. The study was designed to test the hypothesis that older adults may necessitate *longer* periods of time to consciously recognize their errors than younger adults, due to slower information processing speed (see Salthouse 1996). Using similar participant groups as the 1990 study (Rabbitt 1990), three runs of 200 signals were administered at each response-signal interval. Results replicated the findings of the 1990 study and further suggested that the accuracy of error signaling and retrospective error recall increased for both age groups as response signal intervals increased. Error signaling and error correction rates became equitable at 800 ms for young adults and 1,000 ms for older adults, suggesting that while both age groups necessitate additional

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[1] Source-monitoring refers to the ability to recall the temporal and contextual information associated with an episodic memory.

Table 1 Action error handling studies in healthy older adults

Study Authors	Sample	Study Methodology	Neurophysiological and Neuroimaging Results	Behavioral Results
Rabbit 1979	Exp. 1: 15 young adults (*M*=26.2 y) 15 older adults (*M*=64.8y) Exp. 2: 12 young adults (*M*=20.4 y) 12 older adults (*M*=71.3 y)	Serial choice response tasks Exp.1 Error Correction Exp. 2 Error Signaling	N/A	OLD≈YOUNG for error production, signaling, and correction OLD: slower RT for correction and signaling
Rabbit 1990	Four age cohorts: 20 adults aged 20-30 20 adults aged 50-59 20 adults aged 60-69 20 adults aged 70-79	Serial self-paced choice response task 3 groups: Ignore group, Correction group, Signaling Group	N/A	OLD≈YOUNG for error production, post-error slowing, correction OLD < YOUNG for error signaling
Band & Kok 2000	17 young adults (*M*=21.2 y) 13 older adults (*M*=67.3 y)	ERP Mental Rotation Task Condition 1: 45° Condition 2: 135°	OLD < YOUNG: Ne and Pe amplitude	OLD: increased error rate, RT OLD > YOUNG for post-error slowing, Cond. 1 immediate corrections OLD < YOUNG for Cond. 2 immediate corrections
Falkenstein et al. 2001	12 young adults (*M*=22.5 y) 12 older adults (*M*=58.3 y)	ERP 2 tasks: 4 alt-choice reaction task Flanker task	OLD < YOUNG: Ne amplitude	OLD≈YOUNG for error production, correction. OLD: slower RT
Nieuwehhuis et al. 2002	16 young adults (*M*=20.4 y) 16 older adults (*M*=69.6 y)	ERP Exp. 1: Flanker task Exp. 2: Probabilistic Learning task	OLD < YOUNG: Ne amplitude, feedback-related ERN OLD: no condition effect for feedback-ERN amplitude	OLD : increased error rate Exp.1: OLD: slower RT OLD≈YOUNG for post-error slowing Exp.2: OLD≈YOUNG for RT
Rabbit 2002	40 young adults (*M*=20.1 y) 40 older adults (*M*=71.2 y)	Serial choice response task 3 conditions: Correction, Signaling, and Ignore conditions	N/A	OLD≈YOUNG for error production, error correction, and post-error slowing OLD < YOUNG for error signaling. Error signaling accuracy increased for OLD and YOUNG with increased RSIs.
Mathewson et al. 2005	16 young adults (*M*=20.5) 16 older adults (*M*=72.2)	ERP; Dipole Modelling 2 tasks: Flanker task Source memory task	OLD < YOUNG: Ne and Pe amplitude Pe correlated to error production, more sensitive to age effects	Flanker: OLD: increased error rate, RT Source Memory: OLD YOUNG for overall error production.

OLD older adult participants;*YOUNG* young adult participants;*Ne* error-related negativity (ERN);*Pe* error-related positivity;*RT* reaction time

time to consciously evaluate their errors, older adults required significantly more time than young adults. More importantly, this study concludes that older adults are capable of detecting and correcting their errors when provided with additional time. While these studies offer compelling findings on aging and error monitoring, they all hail from the same research group and utilize a relatively simple experimental task. Thus, while older adults demonstrate preservation of function on choice response tasks, it is difficult to discern from these studies whether elderly populations would show comparable performance when tasks are more complex and cognitively taxing.

The Cognitive Neuroscience of Error Handling in Older Adults

The recent surge in neurophysiology and neuroimaging studies provides a corroboratory tool for assessing error handling and has since offered a more complex picture of error detection and correction in young adult populations. However, our literature search yielded no functional neuroimaging studies with healthy older adult participants. Several studies of error detection in healthy older adults have used neurophysiological methods and computational modeling. For example, Band and Kok (2000) suggested that task complexity rather than time restrictions impact older adults' ability to efficiently and accurately handle their errors. In this study, older adults were presented with a mental rotation task (Cooper & Shepard 1973) in which characters were presented in mirrored or normal appearance, and rotated over 45° or 135° clockwise. Inconsistent with documented performance on choice response tasks (Rabbitt 1979, 1990, 2002), older adults generated a higher error rate relative to younger participants, and their accuracy rate failed to improve with increased time. An interesting pattern of performance arose when examining corrective behavior within and between age groups. Older adults offered significantly *more* immediate corrections (proportionally) than young adults on the 45° condition; however, when presented with a more cognitively taxing and complex task, older adults' error corrections plummeted, resulting in proportionally fewer corrections than young adults on the 135° condition. ERP results mirrored the behavioral data; older adults showed significantly reduced error potentials (ERN and Pe) in the complex task condition. Taken together, the study results imply that when older adults detect errors, they are likely to immediately correct them; however, the results do not clearly pinpoint the derivation of difficulty on more complex tasks. It is important to consider that perhaps the complex task was too difficult such that older adults could not determine the identity of the target stimulus and could not generate an accurate internal representation of the correct response. If so, then an error on the complex task would fail to trigger a mismatch between the behavior and an internal representation and would preclude error detection. Without the potential for mismatch, then correction must rely on the external environment. However, responses in the character rotation task do not alter the environment, making detection from an external, environmental mismatch or forcing function impossible. In sum, it is possible that the error handling results may be best explained as a consequence of changes in the nature of errors from the easier to the more difficult condition, with more mistakes and fewer slips in the latter condition.

In a related study, Falkenstein and colleagues (Falkenstein et al. 2001) reported a reduction in ERN amplitude for older adults on a four choice reaction task and flanker task. While they found a diminished correction rate for the most complex condition of the tasks, no significant differences in error correction were noted between age groups. Thus, although the ERP data implied weakened and delayed error detection abilities in older adults, this was not observed in the behavioral data, as older adults' error correction rates were unaffected. These findings again confirm the dissociation between error detection and correction and further underscore the potential for *differential* impairments in these processes. To account for these findings the authors noted the possibility of a threshold effect, such that older adult ERN, although lower than younger adult ERN, were sufficient to trigger error detection and subsequent correction. Another problematic factor in this study may have been the relatively young ages of the selected older adult population; although the authors refer to the older group as "elderly," their ages ranged from only 54 to 65. Gerontology researchers often group this cohort with the "adult" population, thus the findings from Falkenstein and colleagues' study may actually *underestimate* error-handling difficulties in older adults. Alternatively, the aging process may not detrimentally impact automatic corrections, but conscious error detection (i.e. error evaluation / diagnosis) and novel correction behaviors may be diminished.

Altered Error Handling in Older Adults and the Dopamine Hypothesis

In order to elucidate the diminished error-related potentials in older adults described in the aforementioned ERP studies (Band & Kok 2000; Falkenstein et al. 2001), a neurocomputational model was posited (Holroyd & Coles 2002), tested (Nieuwenhuis et al. 2002), and replicated by a separate research laboratory (Mathewson et al. 2005). The explanation put forth by Nieuwenhuis and colleagues (2002) was based on the dopamine hypothesis of reinforcement-learning theory previously described. The model asserts that older age is associated with a "weakened mesencephalic dopamine signal in response to negative (but also positive) violations of basal ganglia predictions" (Nieuwenhuis et al. 2002, pg. 26). This prediction was based primarily on reports of age-related dopamine dysfunction, in which older adults have been shown to have fewer dopamine receptors (Kaasinen et al. 2000) and an associated deterioration in dopaminergic receptor binding in basal ganglia structures (Backman et al. 2000; Volkow et al. 1998).

Before specifically testing this hypothesis, Nieuwenhuis and colleagues (2002) conducted a preliminary study to confirm the age-associated diminution in error-related potentials as well as to rule out other viable explanations for this neural pattern of activity (e.g. deficient representation of the correct response or more mistakes in older adults). The results replicated the age-related ERN waveform effects (i.e., reduced ERN in older adults) in all experimental conditions. Older adults demonstrated no other ERP abnormalities, thus the age-related differences were circumscribed to *error* processing. The results from this preliminary study suggested that the diminished ERN in older adults is *not* simply a function of confusion or failure to formulate a correct response/action plan (i.e., a mistake).

After establishing that the ERN is reduced in older adults, Nieuwenhuis and colleagues (2002) conducted a second experiment using a probabilistic learning task to directly test whether the ERN reduction could be explained by the dopamine hypothesis postulated in Holroyd & Cole's (2002) computational model of reinforcement learning. The investigators assembled a group of "young" and "old" participants to perform a speeded two-choice (right hand vs. left hand) response task with six possible stimuli. Each right *versus* left hand response would yield a 2-cent gain (i.e., reward) or a 2-cent loss (punishment). The stimuli differed according to the degree to which an associated response was prognostic of the feedback value (i.e. 50%, 80%, 100% mappings). That is, for some stimuli, a right hand response would lead to a reward 50% of the time and a punishment 50% of the time. For other stimuli, a right hand response would lead to a reward 100% of the time. However, the participants were not explicitly instructed of the stimulus-consequence mappings; they were instructed to surmise these relations by trial and error. The investigators hypothesized that older adults would demonstrate a reduced ERN because of a weakened dopamine signal in response to unexpected response consequences. The dopamine reduction would result in a decrement in reinforcement from the basal ganglia-ACC system and reduce the older adults' learning curve on this task relative to controls' learning curve. ERN amplitudes also were collected and compared to each group's learning curve. It was suspected that the ERN amplitude would predict learning on the task. Additionally, the authors aimed to fit "younger" and "older" versions of the simulated reinforcement learning models to the observed data.

The results were generally consistent with the dopamine hypothesis of reinforcement learning. Older adults showed diminished learning on the task. Moreover, older adults demonstrated smaller ERN components relative to young participants after erroneous responses (punishment) and after receiving feedback (punishment or reward) from their responses. The authors concluded that the diminished error-related signal in older adults resulted in impaired learning on the task. Furthermore, the learning effects and error handling performance evidenced by older adults were in the same direction as the simulated older adult model, albeit smaller in degree. In conclusion, the authors interpreted the correspondence between their simulated models and empirical results as support for weakened phasic activity in the mesencephalic dopamine system in older adults.

Mathewson et al. (2005) furthered this line of research by investigating error-related ERP components (ERN and Pe) obtained in two tasks that varied with respect to their attentional demands (e.g. flanker task and a more complex source memory paradigm). Older adults demonstrated a reduction in ERN and Pe amplitudes in both tasks, which the authors interpreted as consistent with the dopamine hypothesis of reinforcement learning. Due to the fact that this study was not explicitly testing the dopamine hypothesis, it is difficult to make assertions about the meaning of these findings within the context of Holroyd and Coles' (2002) model, as there are several alternative explanations for reduced ERP signals in older adults that were not evaluated. Interestingly, the amplitude of the Pe, and not the ERN, was substantially lower in response to source memory errors than errors on the less complex flanker task. The Pe task effects were more marked in younger adults; thus while young adults committed fewer errors, their *response* to errors was differentially related to task complexity- a pattern not documented in older adults.

Dipole modeling confirmed these results, as the younger group exhibited a topographical maximum of the Pe that was more frontal on source memory errors than flanker errors. The shift in scalp topography was only reported for young adults, and also was more strongly associated with those participants that adapted more favorably to the different task requirements (i.e., made fewer errors). Older adults engaged a much more distributed neural network associated with the Pe in response to errors relative to their younger counterparts. The results of this study not only confirmed previous assertions of the functional independence of ERN and Pe in error monitoring, but also suggested that older adults may experience a deficiency in the evaluative process of error detection or a reduction in the attentional resources allocated for error monitoring (as indexed by the Pe).

Healthy Older Adults: Conclusions

Recent studies have found that both ERN and Pe amplitudes are diminished in older adults. In addition, although older adults frequently exhibit preserved correction abilities, the neurophysiological indices of error detection appear to be impaired (i.e. diminished). This mismatch between neurophysiological and behavioral data suggests that healthy older adults may be able to perform more automatic corrections, but likely will experience difficulty with complex signaling tasks and tasks that rely heavily on explicit error detection.

At present, there is some support for the reinforcement learning hypothesis to explain the reduced ERN phenomenon. There is some evidence, only in younger adults, that the Pe amplitude may be influenced by task demands. However, given our incomplete understanding of the role of the Pe in error monitoring, it is difficult to make claims about its significance in older adult populations. Moreover, these ERP findings are not easily reconciled with the behavioral data from older adults showing preserved ability to quickly correct errors and post-error slowing with reduced ability to consciously recognize and diagnose (i.e. detection) blunders. Both the ERP and behavioral data continue to suggest a dissociation between detection and automatic error correction. This remains a perplexing facet of the error monitoring process, although it suggests that older adults may exhibit maximal error handling performance on tasks or in environments that facilitate automaticity.

Considering evidence that older adults *can* physically detect and correct their errors in a wide-variety of tasks, it is important to consider factors that may have impacted their performance in the studies reviewed above. One of the many difficulties with tasks such as the flanker, source memory, and 4-choice response task is the multifaceted nature of their design. Young and older adults can ‘fail’ these tasks for a wide variety of reasons, including deficits in visual scanning, attention and concentration, inhibition, and so on. These tasks also are considerably distinct from real-life everyday tasks. Thus, the generalizability of these results to everyday functioning remains unknown.

Another drawback of error monitoring studies in healthy older adults is the relative lack of consensus regarding the definition of “elderly” or “older adult” populations. While 65 represents the typical lower-bound age benchmark in gerontology research, the older adults recruited for these cognitive neuroscience and physiology studies were relatively young. This variability limits our ability to interpret inconsistencies in study findings. To maintain consistency with current gerontology research and ensure reliability of findings, it will be important for future studies to incorporate a cutoff of 65 years or older in their older adult populations.

Finally, the aforementioned studies did not incorporate neuropsychological measures of *gross* cognitive functioning. Several of the studies relied upon an IQ test (Rabbitt 1990), vocabulary test (Rabbitt 2002; Band & Kok 2000; Mathewson et al. 2005; Nieuwenhuis et al. 2002), and/or a self-report health questionnaire (Mathewson et al. 2005; Nieuwenhuis et al. 2002) to ensure that their older adult group was matched to younger participants and was neurologically-intact. However, these methods cannot adequately rule out the possibility of mild cognitive impairment or disease-related changes in neurological functioning in the older adult population. IQ measures may be relatively preserved in older adults with early-stage dementia and self-report questionnaires are not reliable for individuals with memory difficulties. Recent studies of neurologically impaired older adults offer some insight into the impact of mild cognitive deficits on error detection and correction. However, it remains important for future studies investigating normal aging and error handling to ensure that their older sample is indeed “healthy.”

Error Handling and Age-Related Neurodegenerative Disorders

Neurodegenerative disorders, such as Alzheimer’s disease, will affect growing numbers of people as the ‘baby boomer’ cohort ages (Hebert et al. 2001), thus it has become increasingly imperative to understand the functional implications of age-related neurological impairment in older adult populations. Given that *healthy* older adults demonstrate decrements in neurophysiological and, to a lesser degree, behavioral indices of error handling, it is reasonable to assume that *neurologically-impaired* older adults will evidence significant alterations in error detection and correction. Although older adults may experience a wide host of neurological impairments (e.g. stroke; Gehring & Knight 2000; see Ullsperger 2006 for a review of neurological and psychiatric syndromes that affect error handling in patients), the following section will focus on error detection and correction in older adults diagnosed with an age-associated neurodegenerative disorder (e.g. Alzheimer’s disease; Parkinson’s disease). This permits a more specific evaluation of the intersection between aging and neurological disease and its impact on error handling. Table 2 provides a detailed description of error handling studies focused on age-related neurodegenerative diseases. As shown in Table 2, the majority of studies have used neurophysiological methods with traditional cognitive tasks. However, more recently, investigators have examined error detection and correction in complex, everyday tasks in an effort to more directly explicate the clinical significance of monitoring deficits in older adults with degenerative diseases.

Dopamine Hypothesis and Error Handling in Non-Demented Older Adults with Parkinson's Disease

As described earlier, the mesencephalic dopaminergic system has been postulated to play a central role in action error handling (Holroyd & Coles 2002; Nieuwenhuis et al. 2002). The phasic dopamine alterations induced by error activity are imperative for not only detecting and correcting the error, but also modifying future predictions to increase action efficiency. Parkinson's disease (PD) is associated with a degeneration of midbrain dopamine system nuclei, thus this population's ability to detect and correct their errors serves as a crucial test of the dopamine hypothesis. Furthermore, research suggests that in low-level motor tasks, PD participants display faster error corrections after the administration of L-DOPA, suggesting a direct link between error handling and the integrity of the dopamine system (Angel et al. 1970; Angel et al. 1971).

Recent research from Falkenstein and colleagues offers preliminary evidence for the basal ganglia's role in low-level error detection (ERN; Falkenstein et al. 2001), but also suggests that conscious, explicit error-detection (Pe) is not mediated by the dopaminergic system (Falkenstein et al. 2005). In the 2001 study, Falkenstein and colleagues evaluated 15 non-demented idiopathic PD patients and 15 age-matched controls on variations of the Eriksen flanker task, Simon paradigm, and Go/No-Go task. The initial report aimed to ascertain whether low-level error detection, as assessed by the error negativity (ERN), was altered in patients with PD. Consistent with prior studies with healthy older adults, there was no evidence for generalized abnormalities in ERP waveforms or latencies across the groups. Also, the groups exhibited comparable error rates. However, PD participants offered significantly fewer error corrections and demonstrated a marked reduction in ERN amplitude relative to healthy controls across all three tasks. While these findings might imply deficits to the frontal cortex, or more specifically to the ACC, these regions are known to be relatively spared in PD. Therefore, the authors concluded that the source of difficulty must stem from basal ganglia dysfunction (Falkenstein et al. 2001). This finding highlights the interactive role of the ACC and the basal ganglia in action error handling and suggests that a failure in one component of the system can negatively impact evaluative and corrective behavior.

In a follow-up report, Falkenstein and colleagues (2005) utilized the same data from the original 2001 study to address whether conscious error detection, as indexed by the Pe, was also reduced in PD participants relative to healthy older adult controls. In contrast to the reduced ERN amplitude noted previously, PD and healthy control participants showed no significant difference in the Pe component across all three tasks. These findings support the Pe/ERN distinction, but also suggest that the conscious processing of errors is not buttressed by the dopaminergic system.

In contrast to Falkenstein and colleagues' findings (2005), a recent study by Ito and Kitagawa (2006) pointed to a more pervasive error processing deficit in PD. The authors evaluated 17 non-demented idiopathic PD patients and 15 age-matched controls using a lexical decision task, a language based task that requires participants to determine whether the presented stimuli are words or non-words. ERP data indicated that *both* ERN and Pe amplitudes were significantly attenuated in PD patients compared to healthy older adults controls, although the latencies of ERP components were comparable. In addition, PD participants produced significantly more errors on the lexical task while correcting fewer errors than healthy controls. According to Ito and Kitagawa, the combined neurophysiological and behavioral data suggest a deficit in both lower-level and conscious evaluation of errors in PD participants. Given that reduced dopaminergic neurons are a hallmark of PD, the findings are consistent with Holroyd and Coles' dopamine hypothesis of action monitoring (Holroyd & Coles 2002). It's important to highlight, however, that this study employed a language-based task of error monitoring, and thus represents a departure from previous studies of error monitoring in older adults. Although language functioning is relatively preserved in PD, recent studies suggest that some PD patients exhibit compromised speed of lexical activation (Angwin et al. 2007; Grossman et al. 2002). Speed of lexical activation may *partially* explain differences in error rate and conscious evaluation of errors in this study, as the chosen task requires additional processing demands beyond on-line monitoring of performance.

Further complicating our understanding of action error handling in PD, the researchers who proposed the dopamine hypothesis reported preserved error-related potentials in PD (Holroyd et al. 2002). Nine non-demented male subjects with idiopathic PD and 9 healthy controls were administered a modified version of the Eriksen flanker (i.e. horizontal arrow stimuli). No differences were noted in error rate, error correction, or ERN amplitude between PD and healthy control participants. The authors state that the null finding fails to support the dopamine hypothesis of error processing, and suggests that motor and error-related processes are differentially affected by PD. The preservation of error-related processes implies that error detection and correction are not dependent upon the integrity of the mesencephalic dopamine system.

However, the study faced several limitations. First, the authors accurately point out that the deterioration of dopamine nuclei is not spatially uniform, thus some dopaminergic projections remain relatively preserved in early stages of the disease (Haber & Fudge 1997). These

Table 2 Action error handling studies in age-related neurodegenerative disorders

Study Authors	Sample	Study Methodology	Neurophysiological and Neuroimaging Results	Behavioral Results
Falkenstein et al. 2001	15 PD w/o dementia 7 females (M=60.8 y) 8 males (M=62 y) 15 controls (age-matched)	ERP 3 tasks: Flanker task Simon-paradigm Go/Nogo paradigm	PD < CONTROL: Ne amplitude	PD: increased response time PD < CONTROL for error correction
Holroyd et al. 2002	9 PD w/o dementia (M=56.1 y) 9 controls (M=57.3 y)	ERP Flanker task	PD≈CONTROL Ne amplitude	PD≈CONTROL for error rate, response time, correction
Falkenstein et al. 2005	Same data as 2001 study	ERP 3 tasks: Flanker task Simon-paradigm Go/Nogo paradigm	PD≈CONTROL: Pe amplitude	Same data as 2001 study
Ito & Kitagawa 2006	17 PD w/o dementia (M=64.1 y) 15 controls (M=63.8 y)	ERP Lexical decision task	PD < CONTROL Ne and Pe amplitude	PD: increased error rate, response time PD < CONTROL for error correction
Mathalon et al. 2003	12 AD patients (M=76.2 y) 10 Y controls (M=21.2y) 10 O controls (M=75.3 y)	ERP Picture-name verification task	AD < oCONTROL < yCONTROL: Ne amplitude Trend toward AD patients having smaller amp Pe than older controls.	AD: slower RT than both controls
Ito & Kitagawa 2005	16 AD patients (M=65.4 y) 15 controls (M=63.8 y)	ERP Lexical decision task	AD < CONTROL Ne and Pe amplitude	AD: increased error rate, response time AD < CONTROL for error correction
Giovannetti et al. 2002	54 dementia patients (M=76.4 y) 10 controls (M=72.5 y)	MLAT-S	N/A	DEMENTIA: increased error rate DEMENTIA < CONTROL for error detection and correction
Bettcher et al. 2008	53 dementia patients (M=79.5 y) 6 controls (M=75.6 y)	NAT	N/A	DEMENTIA: increase error rate DEMENTIA < CONTROL for error detection and correction DEMENTIA: greater number of microslip corrections than delayed corrections.

AD Alzheimer's disease; *PD* Parkinson's disease ;*Ne* error-related negativity (ERN);*Pe* error-related positivity spared projections (e.g. medial frontal cortex) may be responsible for the lack of difference in error-related potentials in Holroyd and colleagues' (2002) mild to moderate PD sample. Second, the authors did not examine ERP indices of conscious error processing (i.e. Pe), thus the current study cannot specifically address evaluative error detection processes shown to be impaired in other studies (Ito & Kitagawa 2006). Finally, the flanker paradigm implemented in the study is less cognitively taxing than the tasks utilized in studies by Falkenstein and colleagues (Falkenstein et al. 2001; Falkenstein et al. 2005) and Ito & Kitagawa (2006). Individuals diagnosed with mild to moderate PD may not demonstrate pronounced error detection and correction difficulties on less demanding tasks.

In conclusion, recent studies evaluating action error handling in PD and healthy older adult controls have utilized heterogeneous tasks and reported inconsistent findings. As a result, the preservation of error detection and correction processes in PD participants remains questionable. Notably, these studies utilized healthy older adults as controls; however, we know from previous research that healthy older adults exhibit altered error processing and handling. Thus, it is important to underscore that while differences between PD and healthy older adults remain inconclusive, older adults as a whole demonstrate deficient action error handling. It will be important for future studies to incorporate both young and older adult controls to comprehensively evaluate error monitoring deficits in PD. In addition, the previous studies evaluated PD participants who were taking dopaminergic medication, which may have impacted study findings; interestingly, only one study (Holroyd et al. 2002) required an overnight withdrawal (> 12 h) of medication and they reported null findings. Although this suggests that dopaminergic medication may in fact reduce error monitoring, more studies should be conducted with non-medicated PD patients to verify these results.

Alzheimer's Disease and Error Handling

Alzheimer's disease (AD) is characterized by a disruption of the cholinergic and glutamatergic systems, followed by the production of neurofibrillary tangles and senile plaques, which are concentrated in the entorhinal cortex, hippocampus, amygdala and association cortex (Wenk 2006). The neuropsychological ramifications of AD pathology consist of primary impairment in declarative systems, namely episodic memory and semantic knowledge, and secondary deficits in executive control (Knopman & Selnes 2003). These patients' cognitive deficits combined with their impoverished ability to perform everyday tasks (Buxbaum 2001; Giovannetti et al. 2002b) and relative unawareness of deficit (i.e. anosognosia; Green et al. 1993; Vasterling et al. 1995; Vasterling et al. 1997) suggest that AD neuropathology may deleteriously affect action error handling processes. In order to address this concern and elucidate disease-specific changes in error detection and correction, two recent ERP studies evaluated the integrity of action monitoring in AD patients.

First, in a 2003 study by Mathalon and colleagues, 12 AD patients, 10 older adult controls, and 10 young adult controls were evaluated for age- and dementia-related differences in performance monitoring through the administration of a picture-name verification task. This task required that subjects press one button with their preferred hand if the word stimuli matched the picture, and press another button with the non-preferred hand of if they did not match. The error-related potentials garnered from the younger normal controls in the study were consistent with previous studies of the ERN, as the ERN was evident in error trials and peaked around 90 ms after the error response followed by the Pe, which occurred approximately 500 ms after the error. Behavioral results indicated that AD patients demonstrated slower response times than healthy older adults, who were in turn slower than young adults. However, the groups did not differ in the number of errors committed. ERP data showed AD participants demonstrated a reduced ERN amplitude relative to older adult and young controls (AD < older controls < young controls). Although not significant, AD participants also exhibited smaller Pe amplitudes than healthy older adult controls. The authors attributed the reduced ERN amplitude in AD patients to a potentially higher proportion of *mistakes* than *slips*, pointing out that AD participants may retain degraded representations of task knowledge relative to older adult and young adult controls (Mathalon et al. 2003). That is, AD patients and controls may have committed errors for very different reasons. This explanation does not fully explain the noted differences between older and younger controls; the authors speculated that even healthy older adults may exhibit age-related changes in task knowledge. However, the link between reduced ERN amplitudes and degraded word knowledge (or mistakes) was not directly evaluated in this study. A more fine-grained analysis of error correction patterns or additional background testing of word knowledge in AD and healthy older adults might aid in elucidating subtle differences in how the groups respond to their errors.

Ito and Kitagawa (2005) addressed this concern in part by administering a lexical-decision paradigm to 16 AD participants and 15 age-matched controls. Similar to the findings reported in their 2006 study with PD participants, the current study yielded a reduction in both the ERN and Pe amplitude of AD participants relative to healthy older adult controls. AD participants were significantly slower, more error-prone, and less likely to correct their errors than older adult controls. The authors addressed the possibility of increased mistakes *versus* slips, although they highlighted the presence (albeit reduced) of both the ERN and Pe components in 12 out of the 16 participants as evidence that most errors were *not* mistakes. It is not clear whether the authors believe that the 4 participants who did not show discernible ERN and Pe components were committing mistakes rather than slips. Regardless, the observation that 25% of the AD sample did not evidence error-related waveforms in response to blunders is concerning and not specifically addressed in the study discussion. Task knowledge and general semantic knowledge are not dichotomous constructs, thus it is possible that the AD participants in this study had varying levels of semantic degradation. For the 12 participants who exhibited ERN and Pe components, semantic knowledge may have been mildly diminished or spotty, resulting in significantly reduced, but observable error waveforms. Using the same logic, the 4 AD participants who did not show obvious ERN and Pe components may have suffered from disease-related deterioration in semantic knowledge that prevented them from knowing what erroneous output would look like or how to correct it (hence the low correction rate). Without background testing of semantic knowledge, it is difficult to know which processes are responsible for this pattern of results.

Dementia, Naturalistic Action, and Error Awareness

In the midst of a wave of ERP studies, two behavioral studies have examined everyday action error handling and its neuropsychological underpinnings in heterogeneous dementia samples. Giovannetti et al. (2002a) administered the Naturalistic Action Test (NAT; Schwartz et al. 1998, 2002) to 54 dementia participants (including AD, vascular dementia, substance-induced dementia, etc) and compared their performance to 10 healthy older adult controls. Within the context of the NAT, participants are asked to perform 3 tasks with little procedural guidance from the test administrator. The 3 required tasks include: 1) Prepare toast with butter and jelly and prepare instant coffee with cream and sugar; 2) Wrap a gift as a present; 3) Prepare a child's lunchbox with a sandwich, snack, and a drink and pack a child's schoolbag with supplies for school. Performances were videotaped, and error detection and correction were scored. This study showed that individuals diagnosed with a dementia were aware of and corrected a significantly smaller proportion of action errors compared to healthy controls (error detection: 73% for healthy controls, 20% for dementia participants). Furthermore, the authors asserted that while dementia patients corrected a high proportion of detected errors, neither error detection nor correction scores were significantly related to overall dementia severity nor the total number of action errors committed. In other words, neither a general reduction in cognitive resources nor error-prone behavior could sufficiently explain the pattern of results noted in the study. Surprisingly, no neuropsychological measures assessed (e.g executive functioning, language and semantic knowledge, episodic memory, and visuoconstructional skills) were related to action error handling. The authors noted that these null findings might stem from the heterogeneous sample they used, or may be a function of symptom severity, as the participants included in the study were diagnosed with a mild to moderate dementia. Despite the inconclusive findings regarding the neuropsychological bases for error handling difficulties, this study offered an important examination of error detection and correction patterns in the context of everyday activities.

In a follow-up study, Bettcher and colleagues (Bettcher et al. 2008) conducted the first and only examination of microslip corrections in everyday tasks among dementia participants. Microslip corrections are thought to be the most efficient means of correction as they occur before the error is fully executed (e.g. reaching for the wrong item, but stopping oneself before completing the error; Smid et al. 1990; Norman 1981; Giovannetti et al. 2007). Microslips have been attributed to auto-control processes rather than effortful, executive control processes; thus, Bettcher and colleagues were interested in evaluating whether microslips remained preserved in dementia. The frequency of detection/correction in this study was somewhat higher compared to the previous study of only fully committed, overt errors (Giovannetti et al. 2002b); however, even with microslips, the rate of detection/correction was still extremely low in dementia relative to controls (34% and 74%, respectively). Notably, participants corrected the majority of errors they detected (76%), suggesting that the source of difficulty lies in recognizing and/or evaluating the action error (Bettcher et al. 2008). In contrast to previous findings (Giovannetti et al. 2002a), Bettcher and colleagues also found that impoverished performance on tests of executive control predicted a diminution in the ability to efficiently detect and correct mistakes; however, it's important to highlight that executive control measures explained approximately 9% of the variance for error detection, and 11% of the variance for error correction. Bettcher et al. (2008) also analyzed error correction time frames in dementia participants. These analyses revealed that when dementia participants correct their errors, they are more likely to engage in microslip corrections than immediate or delayed corrections. This suggests that auto-control processes are *relatively* preserved in dementia participants and that error detection/correction processes are not substantially slowed. Nevertheless, the overall reduced rate of detections (and corrections) remains concerning and not well characterized.

Age-Related Neurodegenerative Disorders: Conclusions

As a whole, empirical studies of action error handling point to increased response times and reduced *low-level, pre-attentional error detection* (ERN) in neurologically impaired older adult populations (Falkenstein et al. 2001; Falkenstein et al. 2005; Ito & Kitagawa 2006; Mathalon et al. 2003; Ito & Kitagawa 2005). The conscious processing of errors (Pe) remains an empirical quandary, partially owing to our limited understanding of its functional significance in younger adults and partially due to the inconsistent findings noted in recent studies of Parkinson's disease and dementia. Collectively, results suggest that *conscious error detection* is reduced in individuals diagnosed with a neurodegenerative disorder, although future studies are needed to bolster this claim. Of the studies that examined *error correction,* all but one (Holroyd et al. 2002) yielded a reduced error correction rate in neurologically impaired populations, suggesting a limited ability to modify one's behavior upon committing an error. The fact that data ascertained from different neurodegenerative disorders converges to produce strikingly similar patterns of gross error handling is noteworthy. This suggests that while different processes may support error detection and correction, deficits in one (or more) component of this system will result in aggregate declines. While numerous theories have been proposed to explain error-handling deficits (see section on cognitive theories), there has yet to be a comprehensive theory that unifies the data in a clear and parsimonious manner. The dopamine hypothesis (Holroyd & Coles 2002) bears considerable potential, however, it does not directly account for the error detection and correction deficits observed in AD and PD.

Additionally, it is important to highlight the methodological and interpretative difficulties faced by the previous studies on age-related neurodegenerative disorders. First, only one study compared the target sample (neurologically impaired older adults) to both older and young adult controls. Since a variety of tasks were used in these studies, it's important to isolate whether the findings stem from differences in task stimuli or truly represent disease- and age-effects on action error handling. In addition, the use of a single healthy older adult group is not necessarily an ideal control group by which to make comparison, as healthy older adults are also impaired in error handling. Second, with the exception of the studies by Giovannetti et al. (2002b) and Bettcher et al. (2008), most studies fail to address neuropsychological underpinnings of error detection and correction. Although prior ERP studies have isolated monitoring problems, they have not necessarily pinpointed whether these problems reflect a pure error detection and correction deficit or a byproduct of global cognitive dysfunction or impairment in a distinct cognitive process, such as semantic processing. Third, to our knowledge only Giovannetti et al. (2002a) and Bettcher et al. (2008) have examined error handling in ecologically-valid functional tasks.

As summarized in Table 2, only 4 studies included participants with dementia due to Alzheimer's disease or other etiologies. These 4 studies should be summarized separately, as they elucidate monitoring deficits due to dementia. Together these studies suggest that dementia diminishes participants' ability to detect and correct their errors, regardless of the accuracy of their performance. The derivation of this difficulty remains unclear, as the two naturalistic studies reported conflicting neuropsychological results (Giovannetti et al. 2002b; Bettcher et al. 2008). It is possible that the neuropsychological evaluation of a more homogeneous group of dementia participants (e.g. AD) will reveal relations between specific cognitive processes and error handling. For example et al. (2005) and Mathalon and colleagues (Mathalon et al. 2003) addressed the potential impact of degraded semantic knowledge on error detection. However, without systematic evaluation of lexical access and semantic knowledge in AD participants and evidence for a relation between degraded knowledge and reduced error handling, strong assertions cannot be made at this time. Future studies on error handling should include a comprehensive evaluation of task knowledge in order to help identifying whether AD participants are committing slips, mistakes, or a combination of the two, as this speaks to differential impairments in executive control and task knowledge.

Finally, the 4 studies of dementia participants also underscore the need to evaluate the impact of other subtypes of dementia on error handling, particularly frontal-temporal dementia and vascular dementia. Frontal-temporal dementia and vascular dementia frequently result in neuropathological changes in the frontal cortex and are manifested by disproportionate deficits in executive control relative to episodic memory. To the authors' knowledge, there are currently no studies to date that have evaluated action error detection and correction in these diseases exclusively, despite the fact that they likely affect the prefrontal cortex or fronto-striatal processes that subserve action monitoring.

Part 3

Aging and Action Error Handling: Lessons Learned and Future Directions

Considering the relatively recent surge in theoretical and empirical studies of action error detection and correction, it is important to address what we have learned from these studies and how these findings translate to current conceptualizations of error handling in older adult populations. Cognitive neuroscience studies with young adults suggest that when an individual produces a slip (as opposed to a mistake), they demonstrate an error-related negativity (ERN; Gehring et al. 1993), which has been associated with unconscious registration of errors. When a young adult consciously recognizes and diagnoses an error, they typically exhibit an error-related positivity (Pe), which has been associated with the recruitment of frontal cortices and problem-solving processes. Compared with young adults, older adults demonstrate a reduced ability to recognize and diagnose their errors despite the observation that they produce similar rates of correction. Interpreted in the context of young adult study findings, these results suggest that older adults handle their errors best when in an environment that fosters automaticity or routinized responses. It also points to a potential difficulty in handling errors that are generated in environments necessitating controlled responses, as the reduced error detection and diagnosis may render it difficult to generate effective problem-solving strategies. While healthy older adults evidence few *observable* difficulties with error handling, older adults diagnosed with a neurodegenerative disease (e.g. Parkinson's disease; Alzheimer's disease) show a reduced ability to detect and correct their action errors (Falkenstein et al. 2001; Ito & Kitagawa 2006; Bettcher et al. 2008; Giovannetti et al. 2002a). Thus, not only do they demonstrate impairments in registering and diagnosing an error, they also exhibit difficulties in providing automatic and controlled corrections.

This pattern of action error handling is concerning for many reasons. First, it suggests that neurodegenerative illnesses negatively impact lower-level and complex error handling processes. Second, it points to a functional deficit in detecting and correcting problems in the environment that may endanger older adults' ability to safely live alone. Rabbitt (1990) astutely pointed out that older adults frequently live in forgiving environments, in which errors do not engender devastating consequences and thus do not necessitate immediate concern for the older adult; however, recent studies point to a fundamental difficulty in *detecting* action errors, suggesting that older adults are not always in a position to evaluate the immediate danger of their blunder. As a result, they may fail to detect errors that are salient to functional autonomy (e.g. failing to handle errors in financial statements) or safety (e.g. failing to realize that the oven is on). The intimate link between functional autonomy and error processing solidifies action error handling as an important clinical construct that is particularly germane to older adults.

Future Directions

Despite the recent proliferation of studies, numerous gaps exist within the current geriatric action error-handling research. First, no studies to date have evaluated the impact of psychopathology on action error handling in older adults. The role of affective factors in error detection and correction has garnered considerable attention in recent years and holds particular significance for older adults. Cognitive neuroscience studies have reported a larger ERN amplitude in affectively distressed groups, including individuals diagnosed with depression and anxiety disorders (Gehring et al. 2000; Hajcak et al. 2003; Ruchsow et al. 2004). Community prevalence rates of geriatric depression and anxiety range from 1.9% to 9% (Blazer et al. 1991; Wetherell et al. 2005). Taking into consideration the prevalence of psychopathology in older adults, it will be important for future studies to address whether depression and anxiety impacts error-monitoring performance, and elucidate whether these symptoms serve as protective factors or risk factors in geriatric populations.

Second, limited information is available regarding the neuropsychological foundations of error detection and correction. The difficulty in isolating neuropsychological factors originates from the multifaceted nature of study tasks, as well as the frequent exclusion of neuropsychological instruments from study methodologies. Recent studies indicate that error detection and correction may necessitate preserved executive control (Bettcher et al. 2008), a finding that is consistent with the localization of error detection to the anterior cingulate and the hypothesis that error diagnosis results in recruitment of frontal-striatal circuits (Ullsperger & von Cramon 2006). In addition, lapses in attention and concentration also negatively affect the execution of goal-directed behavior (Weissman et al. 2006). A careful evaluation of these processes in the context of action monitoring may shed insight into the error handling difficulties documented in neurologically-impaired older adults. Finally, semantic knowledge and script knowledge may also influence action error handling in older adults. AD and semantic dementia are associated with degraded semantic knowledge; as such, their reduced error detection and correction may partially stem from a diminished understanding of task parameters or reduced access to relevant semantic features of the study task. However, this hypothesis has never been tested directly.

Third, methodological limits challenge our ability to deeply understand the neuropsychological and neurological aspects of error detection and correction. While neuroimaging and neurophysiological studies offer rich data on the neural underpinnings and timing of action monitoring processes, they do not directly address the clinical significance of these deficits. On the other hand, studies of everyday action performance afford the characterization of monitoring behaviors in real-life activities, but they do not directly address neurological substrates. Therefore, future studies must attempt to integrate these diverse methodologies. For example, neuroimaging studies might include tasks that incorporate everyday objects and goals. Neurophysiological methods may be used with real-life everyday tasks where movement requirements are limited. At the very least, researchers using a single method should attempt to present their findings within the context of the broader literature on error monitoring. Furthermore, eye-tracking methods are also a promising approach to the study of error monitoring. For example, eye-tracking methods have been used in studies of everyday tasks and have demonstrated that fixations are tightly linked to task steps/objects and rarely made to objects that are irrelevant to task goals (Hayhoe & Ballard 2005). Thus, eye movements may be useful in determining whether an action error was a mistake (i.e., intended; the error is made with an object that was fixated or scanned) or a slip (i.e., unintended; the error is made with an object that was not fixated or scanned).

An important goal for future research is to distinguish slips from mistakes in older adults diagnosed with a neurodegenerative disorder. The production of an ERN in young adults occurs in circumstances where the individual knows what to do, but fails to provide the right answer (Mathalon et al. 2003). This contrasts with mistakes, in which the individual does not know what to do or doesn't understand the task parameters. Determining whether older adults, particularly those diagnosed with AD or semantic dementia, are primarily producing mistakes or slips represents an important aspect of understanding geriatric error handling deficits. Not only does this issue speak to the derivation of error handling difficulties (e.g. degraded semantic and script knowledge vs. impaired executive control), but it also addresses potential rehabilitation strategies for older adults. For example, AD patients who experience error handling deficits due to diminished task knowledge and semantic information are likely to produce disproportionately more mistakes than slips. Because mistakes are associated with limited opportunities for internal mismatch between expected and actual outcome (Sellen & Norman 1992), AD patients are unlikely to detect and correct their blunders. Rehabilitation strategies would hence aim to increase task and script knowledge with the expectation of subsequently improving error detection and correction (if not error production as well).

Another important goal for future studies is to evaluate environmental influences over error monitoring. There are several reasons why action error handling in everyday life may be qualitatively different than that seen in physiology and neuropsychology studies; however, environmental factors are an obvious difference between these methods. Environmental distractions may reduce error-handling efficiency in older adults, particularly in individuals with executive control impairments (Giovannetti et al. 2007). Alternatively, compensatory mechanisms and environmental affordances (e.g., forcing functions) may actually facilitate action error handling in real life (Gibson 1986), and thus may provide a buffer against neurological changes in error recognition and diagnosis. Future studies should identify the environmental factors that strongly influence error monitoring. Influential environmental factors may be manipulated in an effort to facilitate error monitoring and improve functional behaviors.

In conclusion, the real-world implications of impaired action error handling in older adults are currently unknown. Studies have shown that older adults make more errors on everyday tasks (Schwartz et al. 2002), and caregiver reports of real-life functioning in dementia patients indicate marked deficits in the performance of everyday tasks (Desai et al. 2004). However, it is unclear whether this stems from high error rates, reduced error detection or correction, or a combination of all three. The cognitive neuroscience literature on error handling has the potential to inform and isolate the derivation and manifestation of error handling in healthy and pathological aging. Research that integrates basic and applied approaches to error handling will both advance theories of error monitoring and assist clinicians and caregivers to promote independent everyday functioning in older adults.

Appendix A: Acronym Dictionary

ACC	Anterior Cingulate Cortex
ADL	Activities of Daily Living
ERN	Error-Related Negativity
ERP	Event-Related Potentials
IADL	Instrumental Activities of Daily Living
NAT	Naturalistic Action Test
PD	Parkinson's Disease
AD	Alzheimer's Disease
Pe	Error-Related Positivity

Appendix B

Table 3 Tasks used in geriatric action error handling studies reviewed in Part 2

Task	Description	References
Choice Reaction Task	Several stimuli (e.g. letters or digits) are presented to the participant, and each must be responded to with a specific finger or button. The aim of the test is to induce occasional incorrect responses. Variations of the test include, but are not limited to the following: two and four-choice	Falkenstein et al. 2001; Rabbitt 1979, 1990, 2002

Table 3 (continued)

Task	Description	References
	tasks, self-paced tasks, and speeded tasks with a set response speed interval.	
Eriksen Flanker Task	A target stimuli is presented to the participant, along with stimuli that flank or surround the target. The flankers are either the same as (congruent) or different than (incongruent) the target stimuli. The test aims to induce incorrect responses and slower response times on the incongruent condition.	Eriksen & Eriksen 1974; Falkensteinet al. 2001; Falkenstein et al. 2001; Falkenstein et al. 2005; Holroyd et al. 2002; Mathewson et al. 2005; Nieuwenhuis et al. 2002
Go/NoGo Task	Participants are presented with target stimuli that necessitate a response (Go), as well as stimuli that do not require a response (Nogo). The test aims to elicit incorrect responding to Nogo items.	Falkensteinet al. 2001; Falkenstein et al. 2005
Lexical Decision Paradigm	Words and non-words are presented to the participant, with the instructions being to identify (using buttons) whether the stimulus was a word. Variations include the presentation of 1) a word and 2) a word or a nonword, with the instructions being to determine if item 2) was a word. Speed and accuracy are emphasized in this test.	Ito & Kitagawa 2005, 2006
Mental Rotation Task	A single character is presented to the participant in normal or mirrored versions, and in a variable angle (e.g. 45° or 135° rotation). Participants are instructed to respond as quickly as possible without making a mistake to specific character-mappings. The rotation task permits an increase in task complexity (i.e. mirrored or larger rotation angle) without alterations in content.	Cooper & Shephard 1973; Band & Kok 2000
Naturalistic Action Test	The NAT requires participants to perform 3 everyday tasks with little guidance from the examiner: Item 1) prepare toast with butter and jelly and prepare coffee with cream and sugar; Item 2) wrap a gift while distractor objects that are visually/semantically similar to target objects (e.g., gardening clippers for scissors) are available on the table; Item 3) pack a lunch box with a sandwich, snack, and a drink and pack a school bag with supplies for school, while several of the necessary objects (e.g., knife, thermos lids) are stored out of view in a drawer with potentially distracting objects. Errors as well as the percent error detection and correction are coded from video recordings of performance.	Schwartz et al. 2002; Giovannetti et al. 2002; Bettcher et al. 2008
Picture-Name Verification Test	Participants are presented with a picture for a specified amount of time (e.g. 1 second), followed by a word. Subjects are instructed to press a button with the hand if the word matched the previously seen picture, and press another button with the non-preferred hand if the word did not correspond to the previously seen picture. Semantically-related items are included to increase error responding.	Mathalon et al. 2003
Probabillistic Learning Task	A series of stimuli are presented to participants, and they are instructed to infer stimulus-response mappings by trial and error, utilizing information provided by feedback stimuli at the end of each trial. Stimuli differ in the degree to which the responses are predictive of the values of feedback. The aim is for participants to gradually acquire stimulus-outcome mappings in a probabilistic manner.	Nieuwenhuis et al. 2002
Simon paradigm Task	Stimuli with relevant and irrelevant features are presented to the participant. Subjects are instructed to respond using a particular hand or key to relevant stimuli (e.g. color), while ignoring irrelevant and distracting stimuli or stimulus features.	Falkenstein et al. 2001; Falkenstein et al. 2005
Source Memory Task	A series of common words are presented to subjects, with a forewarning of a subsequent recognition test. The recognition test consists of words from the target list as well as foils, which are intended to appear familiar to the subject despite not appearing on the original study list. This aims to isolate the role of familiarity on target identification.	Mathewson et al. 2005

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