Synchrony Effects in Inhibitory Control Over Thought and Action

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Two experiments explore whether synchrony between peak circadian arousal periods and time of testing influences inhibitory efficiency for younger and older adults. Experiment 1 assesses inhibitory control over no-longer-relevant thoughts, and Experiment 2 assesses control over unwanted but strong responses, as well as performance on neuropsychological tasks that index frontal function. Inhibitory control is greatest at optimal times for both age groups and is generally greater for younger than for older adults. Performance on 2 neuropsychological measures (Stroop and Trails) also changes over the day, at least for older adults, and is correlated with inhibitory indexes, suggesting that for older adults changes in inhibition may be mediated by circadian variations in frontal functioning. By contrast, access to well-learned responses is not vulnerable to synchrony or age effects.

Inhibition is gaining increasing importance in current theories of cognitive psychology as a mechanism critical for control over thought and action (see, e.g., Dagenbach & Carr, 1994; Dempster & Brainerd, 1995; Hasher, Zacks, & May, in press). With respect to control over thought, inhibitory mechanisms are believed to prevent irrelevant or marginally relevant information from entering working memory and to dampen activation of information that was once relevant but later becomes inappropriate for current goals (Hasher & Zacks, 1988; Navon, 1989a, 1989b). For example, inhibition is thought to assist retrieval of weakly activated information in the midst of strong competitors (Dagenbach & Carr, 1994), to suppress inappropriate interpretations of ambiguous words (Gernsbacher & Faust, 1991; Simpson & Kang, 1994; Stoltzfus, 1992), and to dampen no-longer-relevant information (Hartman & Hasher, 1991; Zacks & Hasher, 1994). Thus, inhibition functions to keep thoughts on goal-centered paths.

Inhibition also functions to keep actions goal centered by preventing the production of inappropriate responses (Logan, 1983, 1985). Inhibition holds candidate responses in abeyance until they can be evaluated for their appropriateness and suppresses those responses that are disconfirmed as undesirable. Inhibition is particularly important for control-

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By virtue of its functions in controlling thought and action, inhibition is an essential component of numerous cognitive processes-including selective attention and perceptual recognition, speech production and language comprehension, memory encoding and retrieval, and response control (e.g., Anderson, Bjork, & Bjork, 1994; Arbuckle & Gold, 1993; Dagenbach & Carr, 1994; Gernsbacher & Faust, 1991; Hasher & Zacks, 1988; Logan, 1994; Shapiro & Raymond, 1994; Zacks & Hasher, 1994). By contrast, inefficient inhibition may be a significant contributor to the problems of diminished attention, memory, and control over action that are exhibited by many special populations--including patients with obsessive-compulsive disorder (OCD; e.g., Enright & Beech, 1993; Ferraro, Johnson, & Wonderlich, 1995), children with attention deficit hyperactivity disorder (ADHD; Lorsbach, Wilson, & Reimer, 1995; Schachar, Tannock, & Logan, 1993), and patients with schizophrenia (e.g., Beech & Claridge, 1987; Beech, Baylis, Smithson, & Claridge, 1989). Given the broad impact of inhibitory processing on cognitive functioning, isolating the conditions or variables that affect inhibitory efficiency can have significant implications for a variety of behaviors and populations.

A number of variables are now believed to influence the efficiency of inhibitory mechanisms. Inhibitory efficiency may be reduced by injury to the frontal lobes (e.g., Shimamura, 1995), by depression and stress (Linville, in press), and by the presence of a number of behavioral disorders, including, for example, ADHD (Lorsbach, Wilson, & Reimer, 1995) and OCD (e.g., Enright & Beech, 1993). In addition, inhibitory efficiency follows a developmental course, increasing in childhood and then diminishing in old age (Bjorklund & Harnishfeger, 1990; Dempster, 1992; Hasher & Zacks, 1988; McDowd, Oseas-Kreger, & Filion, 1995; Zacks & Hasher, 1994) and diminishing even further in Alzheimer's disease (Sullivan, Faust, & Balota,

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1995). In the present investigation, we examined the possibility that inhibitory efficiency is also affected by variations in circadian arousal.

The question of whether inhibitory functioning varies with circadian arousal comes from the finding that, like a number of biological processes (e.g., blood pressure, hormone secretion, and body temperature; Horne & Ostberg, 1976; Hrushesky, 1994), aspects of cognitive functioning are governed by individual differences in circadian rhythms (e.g., Bodenhausen, 1990; May, Hasher, & Stoltzfus, 1993), with dramatic changes in cognitive functioning over the day. For example, decisions are more analytic (Bodenhausen, 1990), detection of targets is better (Horne, Brass, & Pettitt, 1980), and recall and recognition of prose are more accurate (May et al., 1993; Petros, Beckwith, & Anderson, 1990) when testing times are in synchrony with individuals' peak in circadian arousal than when they are not. We refer to the finding that performance is optimal when testing times match peak arousal periods as the synchrony effect.

The aim of the present investigation was to explore directly the possibility that inhibitory functioning, as reflected by control over thought and action, is affected by individual differences in circadian arousal. In the two studies reported here, we investigated the impact of synchrony on inhibitory control over thought and action by examining the inhibition of no-longer-relevant information and the inhibition of inappropriate motor responses, respectively, at peak and off-peak times of day.

We examined synchrony effects in two groups of people: college students aged 18–23 years and older adults aged 60–75 years. An age comparison was included here because, relative to younger adults, older adults have been shown to suffer impairments in inhibitory functioning (Hamm & Hasher, 1992; Hartman & Hasher, 1991; McDowd et al., 1995; Stoltzfus, Hasher, Zacks, Ulivi, & Goldstein, 1993), thus raising the possibility that there may be a time at which inhibitory efficiency can be maximized. In addition, this cross age group comparison enabled us to study synchrony effects in two groups with possible baseline differences in inhibitory processing. Thus, the present studies sought to determine whether inhibitory efficiency is influenced by synchrony for both younger and older adults.

We conducted two experiments to investigate the effect of synchrony on inhibition of thoughts and actions. In the first experiment, we used a garden-path procedure developed by Hartman and Hasher (1991) to investigate inhibition of no-longer-relevant thoughts over the day. In the second experiment, we used a stop-signal paradigm (e.g., Logan, 1994) to assess the ability to suppress well-practiced motor responses over the day. Here we also examined performance on two neuropsychological tasks that require overcoming strong, habitual responses and that have been used by others to assess frontal functioning. Finally, in both studies we also explored whether performance was spared on tasks in which strong, prepotent response. Such responses do not require inhibitory control.

There were synchrony effects in both younger and older adults' ability to suppress no-longer-relevant thoughts and inappropriate motor responses. Both groups demonstrated greater inhibitory efficiency at peak relative to off-peak times, and inhibitory efficiency was generally greater for younger than for older adults (see Hartman & Hasher, 1991; McDowd et al., 1995; Zacks & Hasher, 1994). The magnitude of age differences in inhibitory functioning varied over the day, depending on when testing occurred: When younger adults were at their peak but older adults were not, age differences were quite robust; however, when older but not younger adults were at their peak, age differences were reduced and in some cases eliminated. This pattern of synchrony effects was also observed in performance on two standard neuropsychological tasks, and these scores correlated with stopping performance in some instances. These data join with others reported earlier (May et al., 1993) to suggest that age differences on at least some tasks will be exaggerated without careful attention to synchrony effects. Finally, synchrony did not affect performance on all cognitive tasks; specifically, it had virtually no effect on those tasks in which a correct response required the production. rather than the inhibition, of strong, well-learned responses.

Experiment 1

In Experiment 1, we examined people's ability to suppress no-longer-relevant information by using a garden-path procedure (Hartman & Hasher, 1991). For this task, participants generated endings to normatively high-cloze sentences (e.g., "Before you go to bed turn off the . Expected ending: "lights"). For critical sentences, the generated ending (e.g., "lights") was disconfirmed and was replaced by an experimenter-provided target ending (e.g., "stove"), which participants were to remember. The question of interest was whether participants would suppress the disconfirmed endings of critical sentences (e.g., "lights") and remember only the new target endings (e.g., "stove") and whether the ability to do so varied with the synchrony between optimal periods and testing times for younger and older adults. If indeed participants successfully suppress the no-longer-relevant items, they should show access to the new target items but not to the disconfirmed items. Memory for disconfirmed and target items was tested by using an indirect measure that assessed the availability of the two types of critical endings.

Normative Data

Extensive work has suggested age differences in circadian arousal patterns (e.g., May et al., 1993), and so here we began an effort to collect substantial norms on groups from which participants in cognitive experiments are usually drawn. To this end, large numbers of college students (ages 18–23 years) and older adults (ages 60–75 years) were given the Horne–Ostberg Morningness–Eveningness Questionnaire (MEQ; Horne & Ostberg, 1976). The MEQ is a paper-andpencil questionnaire consisting of 19 questions that are designed to examine individuals' sleep–wake behaviors and preferences. Scores on this questionnaire correlate with physiological measures of circadian arousal, such as body temperature, hormone secretion, and pulse rate (Buela-Casal, Caballo, & Garcia-Cueto, 1990; Horne & Ostberg, 1977; Smith, Reilly, & Midkiff, 1989). Furthermore, the MEQ has high test-retest reliability (Kerkhof, 1984), provides a reliable and valid measure of circadian arousal, and has been widely used with both younger and older adults (Buela-Casal et al., 1990; Iren, Adan, & Buela-Casal, 1994; Smith et al., 1989).

Scores on the MEQ classify individuals as one of five types: definitely morning types, moderately morning types, neither types, moderately evening types, and definitely evening types. As can be seen in Table 1, there are considerable differences in circadian arousal patterns across our samples of younger and older adults: Thirty-seven percent of younger adults are evening types, 58% are neither types, and only 5% are morning types. By contrast, only 2% of older adults are evening types, 25% are neither types, and 73% are morning types. These data are in line with findings from other normative studies (e.g., May et al., 1993; Mecacci, Zani, Rocchetti, & Lucioli, 1986) and are consistent with physiological and behavioral data, suggesting a shift toward morningness with age (e.g., Czeisler et al., 1986; Iren et al., 1994; Monk, Reynolds, Buysee, & Hoch, 1991; Tune, 1969; Webb, 1982).

Method

Participants

Forty-eight younger adults (ages 18-22 years) and 48 older adults (ages 62-75 years) participated in this study. Younger adults were Duke University undergraduates, and older adults were volunteers from the Duke University Center for the Study of Aging and Human Development. All participants had peak circadian arousal periods (as assessed by the Horne-Ostberg [1976] MEQ, given to young adults in group testing and older adults through the mail) that were representative of the norms for their age groups: Younger adults were evening types and older adults were morning types. Note that the fully crossed design of Age \times Morningness-Eveningness was not possible because few of our younger adults was an evening type.

Materials

Materials for the sentence completion task were those developed by Hartman and Hasher (1991). In the first phase of the experiment, two types of sentence frames were used: critical sentence frames and filler sentence frames. Twenty-eight sentences with highly

predictable endings (e.g., "Before you go to bed turn off the ." Expected ending: "lights") served as the critical sentence frames. These sentence frames have been normed on younger and older adults, with an approximate cloze value of .85 (i.e., approximately 85% of participants generate the expected ending). For these critical sentences, the high-probable endings served as the disconfirmed items. For each of these critical sentences, a low-probable ending (e.g., "stove" for the example above) was also created to serve as the target. Each low-probable target ending formed an unlikely but plausible sentence (e.g., "Before you go to bed turn off the stove."). The disconfirmed and target endings were relatively equal with respect to frequency of occurrence (Kucera & Francis, 1967), with mean frequencies of 116 and 190, respectively. The set of 28 critical sentences was divided into two subsets, each of which was used equally often in each age group. Thus, each participant viewed 14 critical sentences in Phase 1.

In addition to the critical sentences, 14 filler sentence frames with high-probable endings were also used in Phase 1, and these filler sentence frames were the same for all participants. The 14 fillers were intermixed with the set of 14 critical sentences, with the constraints that 2 filler sentences appeared at the beginning and end of each list of sentences and that no more than 3 critical sentences appeared consecutively. Half of the participants saw one set of 14 critical sentences mixed with the 14 filler sentences; the other participants saw the second set of 14 critical sentences mixed with the 14 filler sentences. Two orders of presentation were created for each subset of sentences, and each order was used an equal number of times in each age group. Finally, each participant began the first phase with 2 practice sentence frames. These practice items also had high-probable endings, and the same practice items were used for all participants.

For each of the 28 critical sentences developed for Phase 1, a pair of normatively moderate-cloze sentence frames (approximate cloze value of .50) was used in Phase 2. One sentence in each pair was moderately predictive of the disconfirmed ending (e.g., "lights") for the corresponding critical sentence, and the other was moderately predictive of the critical target ending (e.g., "stove"). For example, for the critical sentence "Before you go to bed turn off the lights/stove," the following sentences were included in Phase 2: "The baby was fascinated by the bright "(for "lights") and "She remodeled the kitchen and replaced the old " (for "stove"). A total of 56 moderate-cloze sentences were used in Phase 2, and each participant saw every sentence. For each participant, 28 of the medium-cloze sentences could be completed with the critical words from Phase 1 (14 disconfirmed endings and 14 target endings), and 28 could be completed with control words that were not presented in Phase 1. The critical and control items were counterbalanced across participants such that the items that served as critical items for half the participants served as control items for the remaining participants, and vice versa.

Table 1

Distribution of Morningness-Eveningness Scores for Younger and Older Participants

Group	Definite evening (16-30)	Moderate evening (31-41)	Neutral (42–58)	Moderate morning (59–69)	Definite morning (70–86)
Younger adults ^a	6	31	58	5	0
Older adults ^b	0	2	25	51	22

Note. The values given are percentages. The individuals included in this normative study represent geographically and culturally diverse populations, as they were sampled from both large university settings and small college communities in North Carolina, Ohio, Arizona, and South Carolina. $a_n = 1,364$. $b_n = 563$.

Procedure

Half of the participants in each age group were tested in the morning (8:00 a.m.) and half were tested in the early evening (4:00 p.m. or 5:00 p.m.). In this way, half of each age group were tested at their optimal time (i.e., young adults in the evening and older adults in morning), and half were tested at their nonoptimal time (i.e., young adults in the morning and older adults in the evening).

Participants first read 28 normatively high-cloze sentence frames (14 critical and 14 filler) presented individually on a computer screen. Sentences were presented in white font on a black background in the center of a video graphics adaptor monitor. Before each sentence was presented, a fixation cross was presented for 750 ms to help participants focus attention. After the fixation, the entire sentence frame appeared at once, minus the final word. Participants were instructed to generate the most likely ending for each frame. The sentence frame remained on screen until the participant generated an ending into a microphone, and a final word appeared after 400 ms, with the entire sentence and its target ending then remaining on screen for an additional 2,000 ms. For filler sentences, this word was the high-probable, participant-generated ending. For critical sentences, this word was not the participantgenerated ending, but instead was the less-probable ending. Participants were instructed to remember only the word that appeared on screen for a later, unspecified memory test. Thus, for critical sentences, participants were to remember the low-probable target words and could forget the high-probable disconfirmed words. Participants received 2 practice sentences before beginning the learning phase.

After the learning phase, participants were informed that several unrelated tasks would be given before the memory tests. After a brief filled interval, participants completed the indirect memory test for the critical words from the learning phase. Participants were told that the purpose of the indirect test was to create stimuli for a future experiment.

For the indirect test, participants generated aloud endings for 56 medium-cloze sentence frames. Participants read each sentence aloud and generated the first word that came to mind as an ending for the sentence. Each sentence remained on screen until the participant responded, and the experimenter recorded the response. Participants advanced to the next sentence by pressing the spacebar.

The question of interest was whether participants showed priming for the disconfirmed and target endings of Phase 1; that is, did participants complete the critical test phase sentences with the disconfirmed and target endings (e.g., "lights" and "stove," respectively) more or less often than they completed the matched control sentences with the equally likely but, for them, neverpresented endings (e.g., "collar")? After completing the indirect

Table 2

Performance on Noninhibitory Measures (With Standard Deviations in Parentheses) for Younger and Older Adults Tested in the Morning and Evening in Experiments 1 and 2

Group		Experiment	1	Experiment 2			
	ERVT score	High-cloze completions (%)	Medium-cloze completions (%)	ERVT score	Category accuracy (%)	Category RT (ms)	
Young					<u></u>	······	
Morning	17.7 (6.0)	90.3 (7.1)	51.5 (11.1)	18.0 (5.9)	91 (6.0)	939 (132)	
Evening	18.0 (4.9)	90.1 (7.0)	53.2 (11.3)	17.4 (5.7)	92 (6.1)	862 (103)	
Old	,,		,				
Morning	25.8 (5.5)	88.7 (11.4)	48.7 (7.9)	27.7 (7.1)	89 (7.2)	1.170 (251)	
Evening	29.1 (7.6)	87.1 (8.6)	51.1 (9.7)	23.1 (7.4)	91 (9.1)	1,160 (200)	

Note. ERVT = Extended Range Vocabulary Test; RT = response time.

memory test, all participants completed the Extended Range Vocabulary Test (ERVT; Educational Testing Service, 1976), a health questionnaire, and a questionnaire that assessed awareness of the relation between the sentence completion task and the indirect memory test.

Results

For all analyses in this study and in Experiment 2, the alpha level was set at .05 unless otherwise stated.

Participants

Three younger adults (2 tested in the morning and 1 in the evening) and 1 older adult (tested in the morning) reported some awareness of the relation between the two tasks. Their data were replaced with data from 4 new, naive participants. Younger adults (M age = 18.7 years, range = 17–21) had an average of 12.3 (SD = 0.64) years of education, a mean score of 17.9 (SD = 5.4) on the ERVT, and an average MEQ score of 36.1 (SD = 4.9), which placed them in the range of evening types. Older adults (M age = 69.2 years, range = 60-75) had significantly more years of education (M = 15.8, SD = 2.3), F(1, 95) = 125.0, MSE = 2.98; asignificantly higher score on the ERVT (M = 27.7, SD = 6.8, F(1, 95) = 58.67, MSE = 767.10; and a higher mean MEQ score (M = 67.4, SD = 4.8), F(1, 95) = 956.6, MSE = 23.4, which placed them in the range of morning types. There were no main effects or interactions with testing time.

Sentence Completion Rates for Experimental Frames in Phase 1

As seen in Table 2, generation rates for the expected endings of critical sentence frames were 90% and 90% for younger adults tested at optimal and nonoptimal times, respectively, and 89% and 87% for older adults at peak and off-peak times, respectively. Completion rates did not differ across age groups or testing times (all Fs < 1). Although these scores are very close to ceiling, there is little suggestion of a synchrony effect on completion of high-cloze sentences for either younger or older adults; that is, completion rates were no lower at nonoptimal times than at optimal times of day. Note that for all critical sentence frames in which a participant failed to generate the expected ending during the learning phase, the corresponding pair of moderatecloze sentence frames in the indirect memory test were omitted from analyses.

Sentence Completion Rates for Test Phase

The first step in the analysis of completion rates for the test phase was to compare control sentence completion rates for younger and older adults. To this end, a 2×2 analysis of variance (ANOVA) was conducted on completion rates for control sentences only, with age (young vs. old) and testing time (morning vs. evening) as between-subjects factors. Generation rates for the control endings of moderate-cloze control sentence frames were 52% and 53% for younger adults at optimal and nonoptimal times, respectively, and 49% and 51% for older adults tested at optimal and nonoptimal times, respectively (see Table 2). There were no main effects or interactions of age and testing time on control completion rates (Fs < 1.4), suggesting that younger and older adults were equally likely to complete the control sentence frames with the normative endings at each testing time. Thus, the baseline control scores were equivalent for all groups, enabling the remaining tests to be calculated on priming effects (i.e., the difference between target and the control completion rates, and between disconfirmed and control completion rates, with the difference calculated for each participant).

In assessing priming effects, an initial $2(age) \times 2$ (testing time) \times 2 (priming effects) mixed ANOVA was conducted on completion rates. As there was a significant three-way interaction, F(1, 92) = 23.5, MSE = 148.5, remaining analyses were conducted on priming effects for each age group separately. As can be seen in Figure 1, younger adults tested at their peak time (i.e., evening) demonstrated significant below-baseline priming of disconfirmed items (e.g., "lights"; M = -7.6), F(1, 23) = 5.24, MSE = 269.83, and reliable positive priming for target items (e.g., "stove"; M = 11.1), F(1, 23) = 13.36, MSE = 218.22. Thus, at optimal times, younger adults abandoned previously relevant ideas such that those items became inaccessible relative to items that had never been activated in the experimental context and showed facilitated access to target items.

By contrast, younger adults tested at off-peak times (i.e., morning) showed positive priming for both the disconfirmed items (M = 7.6), F(1, 23) = 7.71, MSE = 181.96, and the target items (M = 6.5), F(1, 23) = 4.67, MSE = 220.34. Younger adults tested in the morning thus failed to suppress inappropriate items, enabling both disconfirmed items and new target items to remain active in memory.

Older adults tested at their peak time (i.e., morning) closely resembled younger adults tested at their off-peak times (i.e., morning): They showed significant positive priming for both disconfirmed (M = 5.5), F(1, 23) = 4.23, MSE = 174.31, and target items (M = 10.8), F(1, 23) = 17.44, MSE = 162.42, and these priming scores did not differ from each other by a standard level of significance,



Figure 1. Priming of rejected and target items for each age group and testing time.

F(1, 23) = 1.91, MSE = 177.8, p = .18. These data suggest that even at their peak time, older adults failed to clear from working memory information that was no longer relevant.

When older adults were tested at their nonoptimal times (i.e., evening), inhibitory processing was even further diminished. They demonstrated reliable positive priming for disconfirmed items (M = 12.3), F(1, 23) = 29.04, MSE = 123.34, and actually failed to show evidence of reliable priming for the target items (M = 3.3, F < 1). Note that the priming for disconfirmed items in the evening was marginally greater than that found for disconfirmed items for older adults tested in the morning, F(1, 46) = 3.6, MSE = 170.2, p < .07. Thus at nonoptimal times, older adults had great difficulty abandoning their self-generated responses, and possibly as a consequence, new to-be-remembered target items were no more accessible a few minutes later than words they had not even seen in the context of the experiment.

Discussion

Synchrony between circadian arousal and testing time clearly affects the suppression of inappropriate thoughts for both younger and older adults: Relative to age mates tested at peak times, both younger and older adults tested at off-peak times failed to suppress the disconfirmed, no-longerrelevant items. Younger adults, who elsewhere demonstrate successful inhibitory processing (e.g., Bjork, 1989; Zacks & Hasher, 1994), showed a shift from reliable, below-baseline inhibition of no-longer-relevant items at their peak times to significant positive priming for those items at their off-peak times. Note that in many memory and language-based studies, younger adults show a lack of priming for irrelevant or previously relevant information (e.g., Gernsbacher, 1993; Hartman & Hasher, 1991; for an exception see Simpson & Kang, 1994). They do not typically show the below-baseline inhibition seen here. Thus, the present findings of belowbaseline suppression at optimal times, and of reliable positive priming for disconfirmed items at nonoptimal times, are noteworthy and suggest the possibility that the failure to find below-baseline suppression in earlier studies may have resulted from testing participants at both peak and off-peak times.¹

Older adults, as expected (McDowd et al., 1995; Zacks & Hasher, 1994), showed less overall inhibition of disconfirmed items than did younger adults, but, as for younger adults, the extent of this inhibitory impairment varied dramatically over the day. At peak times, older adults showed significant access to both disconfirmed and target items, indicating that, even at their best times, older adults do not effectively suppress previously relevant but currently inappropriate information. The no-longer-relevant items do not even return to baseline, much less to a below-baseline effect, as seen for younger adults. As further evidence of reduced inhibitory efficiency with age and of synchrony effects for inhibition, note that at off-peak times, older adults showed substantial access to the no-longer-relevant items, coupled with a lack of detectable priming for target items. Thus, age-related inhibitory impairments seen even at optimal times were magnified when older adults were tested at their nonoptimal times.²

The garden-path sentence processing task used here suggests two broad conclusions. The first is that there are age differences across the adult life span in inhibitory efficiency, with heightened performance shown by younger adults. This conclusion is consistent with several other findings of impaired inhibitory functioning in older people (e.g., Hartman & Hasher, 1991; McDowd et al., 1995; Zacks, Radvansky, & Hasher, 1996). The second conclusion, novel to this study, is that for both younger and older adults with strong circadian arousal patterns, there are very strong synchrony effects for inhibitory efficiency. The ability to control thought—in this instance to suppress no-longer-relevant information—is substantially reduced at one's nonoptimal time of day relative to one's optimal time of day, regardless of whether one is a younger or an older adult.

Finally, several findings from the present data, displayed in Table 2, suggest that not all cognitive processes are affected by synchrony. First, in the learning phase, younger and older adults were equally likely to generate the expected endings for high-cloze sentence frames at peak and off-peak times. Second, in the test phase, baseline completion rates for medium-cloze control sentences (i.e., those whose completions were not primed in Phase 1) were equivalent over the day for both age groups. Third, performance on the vocabulary test (ERVT), a measure of semantic knowledge, remained stable across testing times. Together, these data suggest that access to familiar, well-learned information is preserved over the day, even for individuals with strong circadian rhythms (see Anderson, Petros, Beckwith, Mitchell, & Fritz, 1991, for an exception). With respect to control over thought, then, it appears to be the inhibition of irrelevant or distracting information that is affected by synchrony rather than the activation of relevant material, at least if that information is reasonably well known and is tested by using contextual support.

There is one apparent exception to the suggestion that inhibition rather than activation is diminished at asynchronous times, and that is the finding that older adults tested at their nonoptimal time fail to show reliable positive priming for target items. Indeed, because the lack of priming for targets in this condition was surprising, we tested a second group of 16 morning type older adults in the evening. The data from this second group replicate the pattern of reliable priming for disconfirmed items (M = 9.1), F(1, 15) = 7.9, MSE = 73.8, and no reliable priming for target items (M = 4.3, p > .15) for older morning types tested in the evening.

Note that in the garden-path sentence task participants first generate highly probable endings for sentences, some of which (i.e., filler items) they are to remember for a later memory test. The generated items are thus very strong items in the sense that they (a) are highly predicted from the sentence context, (b) are potential target items, and (c) are the first endings that participants produce for each sentence. It is possible that once these highly accessible, strong responses have been generated, older adults at nonoptimal times are unable to disengage from these responses and as a result fail to encode the new, less-probable target items. Support for this notion comes from related work with a similar, directed forgetting paradigm, in which older adults seem to be impaired in their ability to suppress rehearsal of items when a forget cue appears (Zacks et al., 1996). What these findings show is that the presence of a strong competitor in a situation in which the competitor might be right (as it is for half the sentences, i.e., the fillers, in the learning phase) can prevent the easy establishment of a new excitatory connection. Thus the lack of priming for target items shown by older adults at off-peak times may reflect an inability to disengage from the strong, self-generated disconfirmed items and to shift to the new, currently relevant target items.

Considerable evidence from both behavioral and neuropsychological research suggests that the ability to suppress or inhibit strong, prepotent responses and to shift attention from one task or goal to a new task is mediated by the frontal lobes (e.g., Fuster, 1989; Perret, 1974; Shimamura, 1995; Stuss, Estes, & Foster, 1994). For example, heightened response to irrelevant auditory and somatosensory stimuli (Knight & Grabowecky, 1995), diminished inhibition of reflexive but inappropriate saccades (Roberts, Hager, & Heron, 1994), and increased production of irrelevant, offgoal intrusion in speech (Arbuckle & Gold, 1993) are all

¹ In addition, earlier studies may have failed to find belowbaseline suppression because those studies probably included a significant number of neutral-type younger adults, about whose performance little is known.

² It should be noted that Hartman (1995) argued that the sentence completion task used here does not necessarily provide an index of the ability to suppress unwanted information but rather measures the ability to select an ambiguous target (with older adults less able to select in the face of ambiguity). However, only an inhibitory explanation can account for two findings in this experiment: (a) the reliable below-baseline priming demonstrated by younger adults at their peak time and (b) the inability of older adults to switch from their self-generated ending to the target ending at their off-peak time. As well, other evidence suggests that the selection argument is flawed (May, Hasher, Zacks, & Multhaup, 1997).

believed to be related to impaired frontal functioning. It is possible, then, that deficits in inhibitory performance at off-peak times are mediated by changes in frontal functioning over the day. To explore this possibility, we included two standard neuropsychological measures, believed to be frontally mediated, in Experiment 2 to begin an investigation of the effect of synchrony on performance for those tasks and to examine the relation between performance on these frontal measures and on a task requiring inhibition of actions.

Experiment 2

In addition to serving a critical role in the control over thought, inhibitory mechanisms are also believed to enable goal-directed behavior by preventing the production of responses that are inconsistent with current goals. In Experiment 2, we sought to determine whether inhibition of action, as well as inhibition of thought, demonstrates an effect of synchrony. Here, we used the stop-signal paradigm to assess individuals' ability to suppress well-practiced but momentarily inappropriate responses (e.g., Logan, 1983, 1985, 1994; Logan & Cowan, 1984). Again we included both younger and older adults in this study to investigate the effect of synchrony on inhibitory processing for age groups that apparently differ in inhibitory efficiency. We also tested participants on two standard neuropsychological measures, the Stroop (1935) color-naming task and the Trail Making Test (Reitan, 1958), to investigate the effect of synchrony on these measures and to explore the possibility that changes in inhibitory processing may be related to frontal functioning. Finally, we sought to examine the possibility raised in Experiment 1 that performance would be spared over the day for tasks in which inhibition is not a primary determinant of performance.

For the stop-signal task, participants were trained on a primary task in which they judged whether an item (e.g., CHAIR) was a member of a particular category (e.g., FURNITURE) by pressing one of two keys on a computer keyboard. On some test trials, a tone sounded that indicated that participants should withhold their categorization response. The onset of the tone followed the presentation of the category instances at varying delays. This paradigm offers two measures of inhibitory efficiency: (a) success at stopping responses when a tone sounds and (b) the time needed to stop a response. The unique questions addressed here were whether stopping success and rate vary with age, with synchrony, or with both and whether or not the ability to make category judgments is affected by synchrony.

The neuropsychological measures included were the Stroop (1935) color-naming test and the Trail Making Test from the Halstead-Reitan Battery (Reitan & Davison, 1974), both of which are often used to assess frontal lobe functioning (e.g., Grodzinsky & Diamond, 1992; Kimberg & Farah, 1993; O'Donnell, Kurtz, & Ramanaiah, 1983) and have been used extensively as diagnostic tests for neuropsychological dysfunction (Lorig, Gehring, & Hyrn, 1986; Nadler & Ryan, 1984). Each of these tasks requires that participants suppress prepotent response tendencies in order to produce an appropriate response. One advantage of these tasks is that in addition to providing indexes of frontal functioning they provide baseline measures of simple response time that presumably do not reflect frontal processing because the baseline measures are taken for very welllearned responses (color naming in Stroop and connecting numbers in Trails). Thus, we were able to assess synchrony effects both on simple response time tasks and on more complex measures of response inhibition.

Previous research using the stop-signal task suggests that younger adults are generally successful at stopping unwanted responses (e.g., Logan, 1983; Logan & Cowan, 1984) and that older adults are at least slower (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Liu & Balota, 1995) and possibly also less able (Liu & Balota, 1995) than younger adults to stop unwanted responses. On the basis of literature suggesting age (e.g., Hasher & Zacks, 1988; Stoltzfus, Hasher, & Zacks, 1996) and asynchrony (Experiment 1) as sources of inhibitory deficits, we expected that older participants, and those tested at asynchronous times, would be slower and less able to withhold their responses than would younger participants and those tested at synchronous times, respectively. Given previous work demonstrating that older adults are generally slower than younger adults (e.g., Madden, 1992; Salthouse, 1985), and work showing age differences on both the Stroop (e.g., Cohn, Dustman, & Bradford, 1984; Comalli, Wapner, & Werner, 1962) and Trail Making Tests (Wiederholt, Cahn, Butters, & Salmon, 1993), we anticipated that older adults would have slower response times on both the baseline measures and the measures of the Stroop and Trail Making effects. However, given the findings from Experiment 1 suggesting synchrony effects on inhibition but not on well-learned responses, we expected synchrony to impact on only the Stroop and Trail Making effects (i.e., the portions of the tasks that require withholding of responses), not on the baseline measures. As well, on the premise that changes in inhibitory performance may be mediated by variations in frontal lobe functioning, we expected that performance on the inhibitory measures from the stop-signal task would be correlated with the Stroop and Trail Making effects. Finally, on the basis of the findings from Experiment 1, we anticipated that participants would show preserved performance on the category judgment portion of the stop-signal task, a test of well-learned, semantic knowledge, at nonoptimal times of day.

Method

Participants

Thirty-six new younger adults and 36 new older adults were selected from the same populations as in Experiment 1. All younger adults were evening types, and all older adults were morning types. Half of each age group were tested in the morning (8:00 a.m.), and half were tested in the early evening (5:00 p.m.).

Materials

Materials for the categorization task were similar to those used by Logan (1983, 1985). For practice items, 40 category-exemplar pairs were created by selecting 5 exemplars (e.g., CHAIR) from each of 8 categories (e.g., FURNITURE). Twenty "yes" pairs were created by matching category headings with appropriate exemplars (e.g., FURNITURE–CHAIR), and 20 "no" pairs were created by mismatching category headings and exemplars (e.g., FURNITURE–HAMBURGER).

For the experimental trials, 336 different category-exemplar pairs were created by selecting 16 exemplars from each of 21 new categories, using norms collected by Howard (1980). The 5 most frequent exemplars listed for each category and any exemplars that fit into more than 1 category were excluded. Each exemplar was presented only once for a given participant. For each participant, 168 of the category-exemplar pairs were "yes" pairs, and 168 were "no" pairs. Items were counterbalanced such that each exemplar appeared in a "yes" pair and a "no" pair an equal number of times across all participants.

The stop signal was a 500 ms, 900 Hz tone presented through the computer. It occurred on a random 112 (or 33%) of the trials, half of which were "yes" trials and half of which were "no" trials. Presentation of the stop signal was counterbalanced across specific exemplars so that each exemplar was paired with the stop signal an equal number of times across participants in each age group and testing time. Additionally, each exemplar was paired with the stop signal in both a "yes" and a "no" trial an equal number of times across all participants. Thus, a total of six separate experimental lists were created to counterbalance stop signals across both exemplars and responses.

Following methodology suggested by Logan (1994; Logan & Cowan, 1984), the onset of the stop signal was set, for each individual, at three different intervals following the onset of the category stimuli in order to prevent participants from predicting the timing of the stop signal (and hence waiting a fixed amount of time before responding). To compensate for individual and group differences in reaction times, the three stop-signal intervals were set from each participant's mean response time (MRT) on the practice trials as follows: (a) mean practice response time minus 150 ms (MRT - 150 ms), (b) mean practice response time minus 300 ms (MRT - 300 ms), and (c) mean practice response time minus 450 ms (MRT - 450 ms). These intervals were selected so that at the shortest interval (i.e., MRT - 150 ms), stopping was relatively difficult, and at the longest interval (i.e., MRT - 450 ms), stopping was relatively easy, again a decision based on recommendations by Logan (1994).

Materials for the Stroop (1935) color-naming task consisted of three separate pages, each containing different stimulus types: (a) 100 color patches (red, green, and blue), (b) 100 color names printed in black ink (e.g., "red"), and (c) 100 Stroop color words, that is, color names printed in an ink of a different color (e.g., the word "red" printed in blue ink). The color names used on each page were "red," "green," and "blue." The participants' task was to name the stimuli on each page as quickly as possible, and naming time for each page was recorded. For the Stroop color words, participants named the color ink for each item and ignored the written word. The Stroop effect was calculated as the difference in naming time for the Stroop color-word page versus the color-patch page.

The Trail Making Test (Reitan, 1958) consists of two parts, A and B. Part A measures the time required to draw lines connecting numbers that are randomly displayed on a page into a numeric sequence (e.g., 1 to 2, 2 to 3, etc.). Part B measures the time required to draw lines connecting numbers and letters that are randomly displayed into an alphanumeric sequence (e.g., 1 to A, A to 2, 2 to B, etc.). The Trail Making effect was calculated as the difference in time needed to complete Parts B and A.

Procedure

Procedures followed closely to those prescribed by Logan (1994). The experiment began with a block of categorization practice trials, with no mention made of the stopping task. For all categorization trials, a category heading and an exemplar appeared on screen for 700 ms. The category title always appeared above the exemplar, and the participants' task was to indicate whether the exemplar was a member of the category by pressing one of two keys (k for yes or d for no) as quickly and accurately as possible. Response times were recorded. In order to emphasize the importance of the categorization task, no stop signals were presented for the practice trials.

After the practice block, the stopping task was described. Participants were told that on some trials a tone would sound and that for those trials they should attempt to withhold their responses to the categorization task. Participants were further instructed that the tone would occur on only some trials, and then at varying delays, so that sometimes they would be able to stop and sometimes they would not. Finally, participants were told to place primary emphasis on the categorization task and were instructed not to let the stopping interfere with the categorization task. Response time and accuracy were recorded for the categorization trials, and the rate of responding was recorded for stop-signal trials. The experimental trials were divided into four blocks of 84 trials each, and participants had the opportunity to rest between each block as necessary. As participants might have the tendency to slow responding across trials in the stop-signal task, the average response time for the categorization trials was displayed after each block to encourage participants to maintain a consistent speed of responding.

The Stroop color-naming task and the Trail Making Test were administered in their standard formats. Finally, participants were given the ERVT and were debriefed at the end of the experiment.

Results

Participants

Five younger adults (3 in the morning and 2 in the evening) and 4 older adults (2 in the morning and 2 in the evening) failed to follow instructions for the stop-signal portion of the task.³ Their data were omitted from analyses and were replaced with data from new participants. The 36 younger adults (M age = 18.6 years, range = 17-21) had an average of 12.3 (SD = 0.6) years of education, a mean score of 17.5 (SD = 5.7) on the ERVT, and an average MEQ score of 33.1 (SD = 5.1), which placed them in the category of evening types. The 36 older adults (M age = 70.1 years, range = 63-76) had significantly more years of education (M = 16.3, SD = 2.4), F(1, 68) = 101.9, MSE = 3.2, areliably higher score on the ERVT (M = 25.7, SD = 7.2), F(1, 68) = 31.42, MSE = 42.1, and a higher mean MEQ score (M = 67.6, SD = 5.7), F(1, 68) = 694.7, MSE = 30.6,which placed them in the category of morning types. There were no main effects or interactions with testing time for any of these measures.

³ These participants failed to maintain consistent response times for the categorization tasks, as indicated by progressively slower response times across the experiment.

Stop-Signal Task

Stopping probability. Participants' ability to avoid making unwanted responses was calculated as the probability of stopping given the occurrence of a stop signal. Mean stopping probabilities for each age group and testing time are displayed in Table 3. As indicated by a 2 (age) \times 2 (testing time) \times 3 (stop-signal delay) mixed ANOVA, younger adults were more likely to successfully withhold responses (M = 59%) than were older adults (M = 44%), F(2, 136) = 10.1, MSE = 1,339.2. This main effect of age was qualified, however, by an Age \times Testing Time interaction, F(2, 136) = 13.3, MSE = 1,339.2: Younger and older adults did not differ in their stopping probabilities in the morning (F < 1); however, in the evening, younger adults were significantly better at stopping than were older adults, F(1, 34) = 23.6, MSE = 3.05. Planned comparisons indicated that this pattern resulted from the fact that although younger adults' performance improved reliably over the day, F(1, 34) = 10.6, MSE = 3.05, older adults' performance declined significantly as the day went on, F(1,(34) = 3.8, MSE = 3.05.

Consistent with previous research, there was a significant effect of delaying the onset of the signal, with higher stopping probabilities for early onset (i.e., MRT - 450 ms) tones than for late onset (i.e., MRT - 150 ms) tones, F(2,136) = 267.7, MSE = 86.72. There was also a significant Delay \times Age interaction, F(2, 136) = 25.9, MSE = 86.7, which is best understood in light of the significant three-way, Age \times Testing Time \times Delay interaction, F(2, 136) = 4.61, MSE = 86.7. As can be seen in Figure 2, younger adults tested in the morning showed similar improvements in stopping probability across delays to those tested in the evening, with no Delay \times Testing Time interaction, F(2,(68) = 1.47, MSE = 86.7, p > .23. Older adults, however, showed a significant Delay \times Testing Time interaction, F(2,(68) = 4.3, MSE = 86.7, with individuals tested in themorning showing a significantly greater increase in stopping probability across stop-signal delays than those tested in the evening. Thus, in the evening, older adults' performance improved only minimally across delays, whereas those of younger adults improved significantly across delays, result-

Table 3Mean Proportion of Successful Stop Trials and MeanStopping Times (in ms)

	Stopping task					
	Stop proba	ping Ibility	Stop time	ping (ms)		
Group	М	SD	М	SD		
Young						
Morning	.52	.21	282	66		
Evening	.66	.17	248	55		
Old						
Morning	.55	.24	360	80		
Evening	.32	.23	432	161		

Note. For each morning and evening group, n = 18.

Younger Adults + AM Participants PM Participants 0.8 Probability of Stopping 0.6 0.4 0.2 0 **MRT-150 MRT-300 MRT-450** STOP SIGNAL DELAY **Older Adults** 1 AM Participants PM Participants 0.8 Probability of Stopping 0.6 0.4 0.2 0 **MRT-150 MRT-300 MRT-450** STOP SIGNAL DELAY

Figure 2. Mean stopping probabilities across stop-signal delays for younger and older adults tested in the morning and in the evening. MRT = mean response time (in milliseconds).

ing in an increase in age differences from the hardest (MRT - 150 ms) to the easiest (MRT - 450 ms) delay, F(2, 68) = 38.5, MSE = 86.7.

Stopping time. The time required to stop a response at a given stop-signal delay was calculated for each participant following Logan (1994; Logan & Cowan, 1984): Response times on "go" trials were rank ordered from longest to shortest for each participant. Stopping time for a given stop-signal delay was then equal to the response time on the nth "go" trial minus the stop-signal delay, where n = totalnumber of "go" trials (here, 224) times the proportion of successfully withheld responses at a given stop-signal delay. For example, if a participant withheld a response on 50% of the stop-signal trials presented at the (MRT - 150 ms)delay, the stopping time for that delay was equal to the response time for the 112th (i.e., $224 \times 50\%$) longest go trial minus 150. Thus, three separate stopping times (one for each stop-signal delay) were calculated for each participant, and, as estimates of stopping time did not differ across delays, the average of these times was taken as the measure of stopping time.

Mean stopping times for each age group and testing time

are displayed in Table 3. A 2 (age) \times 2 (testing time) ANOVA indicated a main effect of age, F(1, 68) = 30.1, MSE = 9,802.5, with younger adults (M = 265 ms) stopping faster than older adults (M = 396 ms). The magnitude of this age difference varied over the day, however, as indicated by a significant Age \times Testing Time interaction, F(1, 68) = 4.9, MSE = 9,802.5, with significantly larger age differences in the evening (M age difference = 184 ms) than in the morning (M age difference = 78 ms). Although the means for stopping time suggested faster responses in the evening than in the morning for younger adults, this difference was not reliable, F(1, 34) = 2.9, MSE = 9,802.5, p = .10. By contrast, older adults were significantly faster to stop in the morning than in the evening, F(1, 34) = 4.25, MSE = 9,802.5.

Category decisions on go trials. Analysis of performance on go trials, on which participants made a category decision, is important for several reasons. First, category decisions provide a basic assessment of access to semantic knowledge. To investigate the impact of both age and synchrony on the ability to make category judgments, separate 2 (age) \times 2 (testing time) ANOVAs were conducted on mean accuracy rates and reaction times for go trials. Response time was assessed for go trials on which participants responded accurately to the category classification task. For each participant, response times that exceeded the mean response time by 2.5 standard deviations or more were eliminated.

As seen in Table 2, younger and older adults did not differ in their accuracy for category judgments (F < 1), means of 92% and 90%, respectively, although younger adults were significantly faster to respond than were older adults, $F(1, \dots, F(1))$ 68) = 38.4, MSE = 32,760.5. Neither accuracy nor response time showed a main effect of testing time (Fs < 1) or an Age \times Testing Time interaction (Fs < 1). Thus, performance on go trials did not change over the day for either younger or older adults. The lack of an age difference in accuracy rates for category judgments is consistent with other findings of preserved crystallized intelligence with age (e.g., Cunningham, Clayton, & Overton, 1975; Lachman & Jelalian, 1984), and with the finding in Experiment 1 of equivalent performance for younger and older adults on medium- and high-cloze sentence completion tasks. The age difference in response time is consistent with other findings that indicate that older adults are generally slower than

younger adults (e.g., Madden, 1992; Salthouse, 1985). Finally, the lack of a synchrony effect for either accuracy rates or response times is consistent both with the data from sentence completion tasks and with the vocabulary scores in Experiments 1 and 2 in suggesting that access to and retrieval of well-learned, semantic information is preserved at nonoptimal times, and furthermore that the speed of retrieval of highly familiar information is stable over the day for both younger and older adults.

A second reason for examining performance on go trials was to assess performance on category decisions across the experiment. Because the stop-signal paradigm is a dual-task paradigm that requires individuals both to perform the categorization task and to stop when a tone sounds, it is critical that participants maintain consistent performance on go trials across the entire experiment, as variations in performance on go trials can affect stopping performance. That is, if participants vary the emphasis placed on category decisions relative to stopping, their stopping performance will also change. Such changes would be particularly problematic if they were more likely in one age group or at one testing time. To examine go trial performance across the experiment, we compared accuracy and response time for the first half of the experiment with that for the second half of the experiment. Analyses indicated no difference in accuracy rates or response times across the experiment for younger and older adults at either testing time (Fs < 1). Thus, performance on go trials remained stable across the experiment for all participants. Furthermore, to assess whether the addition of the stopping task affected performance on the go trials, we compared response times for the experimental trials with response times for the final 20 practice trials, in which participants did not perform the stopping task. Participants were slightly but not significantly faster on the experimental trials, indicating that they maintained emphasis on the category decisions as instructed and that category decisions were not affected by the addition of the stop-signal task. This pattern was consistent across age groups and testing times.

Neuropsychological Measures

Stroop task. Mean naming times for the color and Stroop cards are displayed in Table 4. To assess the effect of age and testing time, response times for each card were

Table	4
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Naming Times (With Standard Deviations in Parentheses) in Seconds for Stroop and Trail Making Measures by Age and Testing Time

_			-				
Group	Color	Word	Stroop	Stroop effect	Trails A	Trails B	Trail effect
Young			······································				
Morning	54.6 (9.3)	43.3 (6.9)	95.1 (11.6)	40.5 (8.1)	21.4 (4.0)	52.6 (12.6)	31.2 (11.4)
Evening	51.7 (7.3)	38.4 (4.0)	86.3 (16.5)	34.6 (15.3)	21.2 (5.2)	44.8 (7.2)	23.6 (7.3)
Old		• •	· · ·	. ,		. ,	
Morning	60.2 (9.9)	44.7 (10.3)	113.0 (23.3)	52.8 (21.7)	29.9 (8.0)	62.5 (17.9)	25.6 (14.3)
Evening	61.5 (9.2)	48.4 (6.3)	126.4 (23.6)	64.9 (21.0)	30.4 (8.1)	78.3 (26.7)	47.9 (25.0)

Note. For each morning and evening group, n = 18. Trails = Trail Making Test.

assessed with a 2 (age) \times 2 (testing time) ANOVA. For the color card, younger adults were significantly faster than older adults in naming color patches, F(1, 68) = 12.5, MSE = 80.5. There was neither a main effect nor an interaction with testing time (Fs < 1), suggesting that synchrony does not affect the speed of naming color patches for younger or older adults.

For the word card, younger adults were significantly faster than older adults, F(1, 164) = 26.3, MSE = 41.7. Although there was no main effect of testing time, there was an Age \times Testing Time interaction, F(1, 164) = 11.8, MSE = 41.7: Younger adults were significantly faster in the evening than in the morning, F(1, 82) = 7.7, MSE = 41.7, whereas older adults were faster in the morning than in the evening, F(1, 82) = 4.4, MSE = 41.7. As a result, younger adults were reliably faster than older adults in the evening, F(1, 82) = 37.0, MSE = 41.7, but not in the morning (F < 1).

For the Stroop card, there was a main effect of age, F(1, 68) = 38.4, MSE = 374.9, with younger adults significantly faster than older adults. There was no main effect of testing time, but there was a reliable Age \times Testing Time interaction, F(1, 68) = 5.7, MSE = 374.9, such that younger adults showed no effect of testing time on Stroop naming, F(1, 68) = 1.8, MSE = 374.9, p > .15, but older adults were significantly faster in naming Stroop words at their peak time than at their off-peak time, F(1, 34) = 4.1, MSE = 374.9.

The Stroop effect was calculated as the difference in response time for the Stroop card versus the color-patch card. As expected, younger adults (M = 37.5 s) showed a reliably smaller Stroop effect than did older adults (M = 58.9 s), F(1, 68) = 26.0, MSE = 299.2. There was no main effect of testing time, but there was an Age \times Testing Time interaction, F(1, 68) = 4.7, MSE = 299.2, with significantly larger age differences for the Stroop effect in the evening (M age difference = 30.3 s) than in the morning (M age difference = 12.3 s). Planned comparisons indicated that there was no difference in the Stroop effect for younger adults across the day (F < 1), but older adults demonstrated a reliably greater Stroop effect in the evening (M = 65 s) than in the morning (M = 49 s), F(1, 34) = 4.2, MSE = 299.2.

The Trail Making Test. Response times for Parts A and B of the Trail Making Test are presented in Table 4. A 2×2 ANOVA was conducted to assess the effects of age and testing time on performance for each part. For Part A, younger adults (M = 21.3 s) were significantly faster than older adults (M = 30.2 s), F(1, 68) = 32.5, MSE = 42.8. As with the color card of the Stroop task, there was neither a main effect of testing time (F < 1) nor an Age \times Testing Time interaction (F < 1). These data suggest that synchrony had no impact on individual's speed for connecting dots in numeric order, as it had no impact on color naming in the Stroop task.

For Part B, younger adults were again faster than older adults, F(1, 68) = 25.9, MSE = 307.8, but there was no overall effect of testing time. There was an Age \times Testing Time interaction, F(1, 68) = 7.9, MSE = 307.8, with a

significantly greater age difference for Part B in the evening (M age difference = 33.5 s) than in the morning (M age difference = 9.9 s).

The Trail Making effect was calculated as the difference in response time for Part B versus Part A. Younger adults (M = 19.2 s) showed a reliably smaller effect than older adults (M = 52.3 s), F(1, 68) = 10.9, MSE = 250.0, with no testing time effect (F < 1). There was a significant Age \times Testing Time interaction, F(1, 68) = 9.1, MSE = 250.0, with younger adults showing no effect of testing time F(1, 34) =1.9, p > .15, MSE = 250.0, and older adults demonstrating a significantly greater Trail Making effect in the evening than in the morning, F(1, 34) = 8.2, MSE = 250.0. Furthermore, the age difference for the Trail Making effect was reliable in the evening (M age difference = 24.3 s), F(1, 34) = 19.9, MSE = 250.0, but not in the morning (M age difference = 1.4 s, F < 1). Thus, synchrony effects were consistently found for those aspects of the Stroop and Trail tests that require suppression of strong but inappropriate responses but were not evident when production of a welllearned response produced a correct answer.

Correlations with stop-signal measures. A Pearson product-moment correlation analysis was conducted to explore the relation between performance on the Stroop and Trail Making tests and our indexes of inhibition (i.e., stopping probability and stopping time) for younger and older adults. As can be seen in Table 5, younger adults demonstrated a significant relation only between the Stroop effect and stopping probability (r = -.33). The lack of a consistent relation between the inhibitory and the neuropsychological measures for younger adults was somewhat surprising and most likely resulted from the limited range of scores demonstrated by younger adults for each of the measures, most notably the Trail Making effect and stopping time.

For older adults, the Stroop effect correlated reliably with both stopping probability and stopping time (r = -.33 and .56, respectively), indicating that individuals with the largest Stroop effects were also the least successful and the slowest at stopping unwanted actions. Similarly, there was a significant correlation between the Trail Making effect and stopping probability (r = -.50) and between the Trail Making effect and stopping time (r = .60), indicating that, as with the Stroop, individuals with the largest Trail Making effects were the least likely to inhibit unwanted actions. Finally, the Stroop and Trail Making effects showed a significant correlation of .55, as one might expect if the two tests reflect similar underlying processing.

Discussion

The data from Experiment 2 indicate that inhibitory efficiency, here assessed by the speed and accuracy of stopping a category judgment, varies over the day for younger and older adults, with younger adults at their peak in the evening and older adults at their peak in the morning. Furthermore, testing time critically influences the pattern and magnitude of age differences observed, at least for tasks involving inhibition. Although older adults generally showed impaired performance relative to younger adults, this age-

Variable	1	2	3	4
	Youn	ger adults		
 Stopping probability Stopping time Stroop effect Trail Making effect 		39* _	33* .16 	06 .07 .04
	Olde	er adults		
 Stopping probability Stopping time Stroop effect Trail Making effect 	_	- .58*	33* .56*	50* .60* .55*

Table 5Correlations Among Inhibitory Indexes and Neuropsychological Measures for Youngerand Older Adults

*p = .05.

related impairment was small and, in some instances, unreliable in the morning but was consistently robust in the evening. This pattern resulted from the fact that the performance of younger adults improved across the day, whereas that of older adults generally deteriorated as the day progressed.

In addition to the synchrony effect on the inhibition of action, changes in performance over the day were also observed for two standard neuropsychological tasks associated with frontal functioning, at least for older adults. As well, performance on these neuropsychological tasks was correlated with inhibitory measures for older adults, suggesting the possibility that decrements in inhibitory processing at off-peak times may be related to changes in frontal functioning. Finally, as in Experiment 1, there was evidence that tasks that require the use of well-learned information such as simple categorization, vocabulary measures, and color naming—are relatively unaffected by the match between arousal periods and testing times.

Consider first the findings regarding synchrony effects and inhibition of action. Two key measures assessed the efficiency of controlling action, or inhibiting inappropriate motor response: (a) the probability of stopping an unwanted response and (b) the time required to do so. With respect to stopping probability, the data indicate that control of action is optimal when testing occurs at the peak time of day, which in the present instance was the morning for older adults and the evening for younger adults. The data also demonstrate that in addition to an overall age difference favoring younger adults in suppressing actions, the magnitude of this difference can be altered by testing participants at different times of the day: In the morning, when older but not younger adults were at their peak, the age difference in inhibitory efficiency was unreliable; in the evening, however, which was the peak for younger but not older adults, the age difference in inhibitory functioning was quite robust.

Consistent with previous research (e.g., Logan, 1983, 1985, 1994), stopping probability decreased for both younger and older adults as the onset of the tone was delayed to a time increasingly close to the natural onset of a category response. This finding indicates that, as expected, the greater

the delay between the presentation of the category stimuli and the onset of the tone, the more difficult it was for participants to stop their responses. One unexpected finding, though, was the change in the magnitude of age differences across delays when participants were tested in the evening. Specifically, the age difference in stopping probability decreased as the onset of the tone increased, suggesting that as the task became more difficult, the performance of younger and older adults was more similar. This pattern is noteworthy because other works suggest an increase in the magnitude of age differences with increasing task difficulty (e.g., Birren, 1956; Clay, 1954; Crowder, 1980).

One possible explanation for these data is that older adults tested in the evening are simply incapable of suppressing strong responses, even when the task is relatively easy. Note that in the evening the performance of older adults improved only slightly over delays relative to the improvement shown by younger adults, resulting in an increase in age differences with earlier delays. That is, older adults in the evening were so impaired that even with very early stop signals (i.e., MRT - 450 ms), they stopped only 40% of the time, whereas younger adults, by contrast, stopped 88% of the time. Together with the finding in Experiment 1 that older adults in the evening could not acquire a new response in the face of a strong competitor, these findings suggest that, in both thought and action, older adults in the evening have great difficulty abandoning strong or prepotent responses. This inability to abandon old learning is very likely to make the acquisition of new responses very difficult.

With respect to the time required to stop unwanted responses, the data suggest testing time may not be a significant determinant of younger adults' overall speed of suppressing unwanted responses. However, testing time does affect the speed with which older adults can suppress or stop inappropriate actions; they are faster at their optimal time of day. These findings suggest that the impact of synchrony on younger adults' performance may not be as strong or as consistent as it is for older adults.

Together, then, the data from the two critical measures of inhibitory functioning used here suggest (a) that younger and older adults demonstrate diminished response control at nonoptimal times of day and (b) that older adults are generally less efficient than younger adults at suppressing unwanted actions. In addition, the present data demonstrate dramatic changes in the magnitude of age differences in inhibition over the day. Although older adults were generally impaired in their ability and speed of stopping unwanted responses relative to younger adults, the extent of this impairment was greater in the evening than in the morning. Specifically, the robust age differences in stopping probability found in the evening were not significant in the morning, and, furthermore, the large age difference in stopping time in the evening was reduced reliably by more than 50% in the morning.

The present data thus replicate earlier reports of overall age differences in inhibitory functioning (e.g., Hasher & Zacks, 1988; McDowd et al., 1995; Zacks & Hasher, 1994) and particularly in stop-signal performance (Kramer et al., 1994; Liu & Balota, 1995). Furthermore, the present data also offer an explanation for discrepant findings in prior stop-signal work. Note that Liu and Balota found age differences in both stopping probability and stopping time measures, although Kramer et al. found significant age differences only in stopping time. It is possible that Liu and Balota tested many of their participants in the late afternoon, or at least not in the morning, as their data closely resemble the pattern of data for participants tested in the evening in the present study. On the other hand, Kramer et al. may have tested the majority of their older adults in the morning, as older adults tested in the morning in the present study showed equivalent stopping probabilities but slower stopping times than younger adults.

There is one alternative explanation, however, for the finding of age and testing time effects on stopping ability that should be considered. In this experiment, the three stop-signal delays were set according to the mean response time for each individual, without regard to individual or group differences in the variability of response times. It is possible that the observed differences in stopping ability resulted not from diminished inhibition but rather as an artifact of greater variability in response times for older adults and individuals tested at off-peak times: With more variable responding, the 150-ms intervals for each stop signal will cover different amounts of the response time distribution, possibly exaggerating differences in stopping ability. To examine the possibility that response times were more variable for older adults and those tested at off-peak times, we assessed whether there were age and testing time effects on the standard deviations in go trial response times. There was a main effect of age, with older adults having a higher average variance in go response times (M = 261 s)than did younger adults (M = 210 s), F(1, 68) = 10.6, MSE = 4,259.4. However, there was no effect of testing time, and importantly, no Age \times Testing Time interaction. Thus, although increases in response variability may have contributed to age differences in stopping ability, they cannot account for effects of testing time on performance for either younger or older adults. Furthermore, increased response variability cannot account for either age or testing time differences in stopping time, suggesting that there are true group differences in the ability to stop unwanted actions.

In addition to synchrony effects in inhibitory processing, changes in performance over the day were also evident in both the Stroop and Trail Making effects, at least for older adults. Note, importantly, that these changes occurred in the absence of differences across the day in the baseline measures for these tasks, and thus the increased effect sizes at off-peak times cannot be attributed to general slowing. These findings indicate that, for older adults, synchrony effects are evident for two standard neuropsychological tasks that are often used to assess frontal functioning, raising the possibility that changes in performance over the day may be frontally mediated. The notion that frontal functioning may underlie changes in inhibitory performance at off-peak times is further supported by the finding of significant correlations between the frontal measures and the inhibitory measures for older adults. These findings are only preliminary and suggestive, however, as concerns have been raised regarding the validity of both the Stroop and Trail Making tests as indexes of frontal processing per se (Blenner, 1993; Reitan & Wolfson, 1995). Certainly further behavioral and imaging research is needed to discern the locus of synchrony effects within the brain. Regardless of underlying mechanism, though, the finding that performance on the Stroop and Trail Making tests changes over the day is of particular importance for neuropsychologists and clinicians, who often use these tasks as screening and diagnostic tools (e.g., Greenlief, Margolis, & Erker, 1985). If the time of day and individual differences in circadian arousal are not considered for individual testing sessions, then comparisons of individual scores to standardized norms may be inappropriate. Indeed, it is unclear how to interpret the current norms, as presumably time of day was not controlled for in their collection. Finally, for test-retest measures, in which the performance on the same task is assessed over different testing sessions, testing time must be controlled across sessions, or the differences (or lack thereof) observed between test scores may be misleading.

With respect to the performance of younger adults on the neuropsychological measures, the testing time effect was not significant for either the baseline or effect size measures in either task, although the means were in the direction of better performance at peak relative to off-peak times for the effect size measures. These findings, along with the lack of testing time effect for the stopping time measure of the stop-signal task, suggest that synchrony effects may be less consistent, less powerful, or both for younger than for older adults. The failure to find significant correlations between the neuropsychological and the inhibitory measures most likely resulted from the limited range of scores on the neuropsychological measures.

Finally, we consider younger and older adults' performance over the day for noninhibitory tasks, where production of a well-practiced or familiar response resulted in a correct answer. In contrast with the dramatic synchrony effects for inhibitory tasks, there were no testing time effects for either age group on the accuracy or the speed of category judgments, in vocabulary scores, or on the baseline measures of the neuropsychological tests. Because the categories used in the stop-signal task were familiar categories and the exemplars were relatively common instances for each category, participants could rely on well-practiced, familiar knowledge in making their judgments. Similarly, vocabulary performance reflects access to well-learned, semantic knowledge, and color and number identification require retrieval of highly practiced information. These data then, in conjunction with the data from the high- and medium-cloze sentence completion rates and the vocabulary data in Experiment 1, further the suggestion that access to well-learned, semantic information is preserved at off-peak times of day.

General Discussion

The central question explored in this investigation was whether the synchrony between peak circadian arousal periods and testing time influences the ability to inhibit inappropriate thoughts and actions. A secondary aim of this research was to examine the impact of synchrony on inhibitory functioning in older adults, for whom peak periods of inhibitory efficiency may be particularly significant, given age-related deficits in inhibitory processing (e.g., Dempster, 1992; Hasher & Zacks, 1988; McDowd et al., 1995). In addition, we investigated whether performance on two standard neuropsychological measures varied over the day and explored the relation between these measures and our indexes of inhibition. Finally, we investigated whether performance was spared at off-peak times for tasks requiring production of strong or well-learned responses. Across two experiments, the data offer clear answers to each of these issues.

First, inhibitory control over thought does demonstrate a strong synchrony effect in both younger and older adults, with both groups showing diminished ability to clear no-longer-relevant information from working memory. For younger adults, impairments in inhibitory functioning resulted in a shift from reliable, below-baseline suppression of no-longer-relevant information at optimal times to positive priming of that information at nonoptimal times. Indeed, the performance of younger adults tested at their off-peak time closely resembled that of older adults, who have been shown elsewhere to suffer age-related deficits in inhibitory functioning (e.g., Hasher & Zacks, 1988; McDowd et al., 1995; Stoltzfus et al., 1996; Zacks & Hasher, 1994). Testing younger adults at nonoptimal times, then, may become an important tool for understanding and predicting the behavior of older adults---in a sense, a human model of aging.

For older adults, inhibitory impairments at off-peak times resulted in heightened priming of no-longer-relevant information as well as diminished priming for new, currently relevant material. Note that the consequences of diminished inhibition at off-peak times were especially devastating for older adults, as the inhibitory impairment found at off-peak times was compounded by age-related deficits in inhibition. Consistent with earlier work (e.g., Hasher, 1994; Hasher & Zacks, 1988; Hasher, Zacks, & May, in press; McDowd et al., 1995; Stoltzfus et al., 1993), older adults in the present study showed a general deficit in inhibitory functioning relative to younger adults, although the magnitude of this age difference changed substantially over the day. In the morning, when older but not younger adults were at their peak, age differences in inhibition were eliminated; in the evening, which was the peak for younger but not older adults, inhibitory control over thought was greatly impaired in the older relative to younger adults.

For both age groups, deficits in inhibitory control over irrelevant or distracting thoughts at nonoptimal times may have widespread implications, as inhibition is believed to play a central role in narrowing activation to only contextually appropriate interpretations of words (e.g., Gernsbacher, 1993; Simpson & Kang, 1994; Stoltzfus, 1992), in rejecting erroneous interpretations of garden-path passages (Hamm & Hasher, 1992), in preventing off-track intrusions in speech (Arbuckle & Gold, 1993), and in retrieving weakly activated items from long-term memory (Dagenbach & Carr, 1994). Indeed, deficits may be expected at off-peak times for any tasks that rely heavily on working memory, as inhibitory processes are believed to prevent irrelevant information from entering working memory and to clear information from working memory that was at one point relevant but is no longer appropriate (Hasher & Zacks, 1988).

The second critical finding from the present work is that in addition to impairments in control over thought at nonoptimal times, inhibitory control over action also showed impairments at nonoptimal times, with both younger and older adults showing a reduced ability to prevent production of inappropriate responses at nonoptimal times of day. Younger adults showed a decreased probability of stopping unwanted actions at off-peak times, and, as in Experiment 1, their off-peak performance closely resembled the performance of older adults tested at their peak time. For older adults, both the ability to stop inappropriate responses and the speed of stopping were impaired at nonoptimal times, as was performance on two standard neuropsychological measures, indicating that the impact of synchrony on inhibitory functioning may, in some cases, be greater for older than for younger adults. As expected, older adults were impaired in their ability to inhibit unwanted actions relative to younger adults (Kramer et al., 1994; Liu & Balota, 1995). Furthermore, performance on inhibitory measures correlated with the Stroop and Trail Making effects, consistent with the notion that inhibitory processing may be frontally mediated and that changes in inhibition over the day may result from circadian variations in frontal functioning. Finally, as in Experiment 1, the extent of age differences for both the inhibitory and neuropsychological measures varied over the day, with minimal age differences in the morning and robust age differences in the evening.

The finding of dramatic variations in the magnitude of age-related inhibitory deficits over the day has profound implications for researchers investigating group differences in inhibitory functioning, particularly if the groups of interest are those who have different circadian arousal patterns. As with the present data, changes in inhibitory efficiency may be either underestimated or exaggerated, depending on when during the day participants are tested. These findings are consistent with earlier work showing that conclusions about age differences in episodic memory retrieval can also be substantially impacted by the time of testing (May et al., 1993).

In addition, the finding that older adults show reliable differences over the day on two neuropsychological measures holds significant practical and theoretical implications for clinicians, neuropsychologists, and cognitive gerontologists. Time of testing must be considered in the administration of these tests to allow appropriate assessment of behavior in both single-test and test-retest situations. It is also possible that normative data need to be reevaluated with testing time controlled.

Finally, it is important to note that synchrony did not affect performance globally, as synchrony effects were not reliable for several of the measures assessed in the present investigation. First, generation of both highly and moderately predictable sentence endings was equivalent at optimal and nonoptimal times for younger and older adults. Also, both age groups were as fast and accurate at off-peak times as they were at peak times in making category judgments about familiar items across the day, in naming colors, in connecting dots in numerical order, and in defining vocabulary words. Note that these findings are consistent with an inhibitory framework, in which the major function of inhibition is to control strong but situationally inappropriate responses. The findings thus suggest that whenever strong responses are correct, individuals can rely on this information to mediate successful performance at off-peak times of day.

In summary, then, synchrony effects clearly influence inhibition, a process critical for the control of thought and action. Synchrony effects were evident for younger and older adults across several different measures of inhibitory functioning, with both groups performing better when tested at their respective optimal times. Younger and older adults who differ in their peak arousal periods will show robust age differences in the evening, and these differences can be significantly reduced and even negligible in the morning. Finally, not all processes are equally susceptible to synchrony effects, as retrieval of well-learned responses seems to be preserved over the day. Instead, it is the blocking of such responses, when they are inappropriate (Experiment 2) or no longer relevant (Experiment 1), that seems to be disproportionately disrupted at nonoptimal times.

Thus, the synchrony between circadian arousal periods and testing times joins with other factors including stress and depression (Linville, in press), age (Dempster, 1992; Hasher & Zacks, 1988), frontal lobe functioning (Arbuckle & Gold, 1993; Shimamura, 1995), and certain psychological disorders (e.g., Beech & Claridge, 1987; Ferraro et al., 1995) as an important influence on the efficiency of inhibitory mechanisms. The present data suggest that inhibitory efficiency is significantly impaired at nonoptimal times for younger and older adults, resulting in reduced control over distracting or extraneous thoughts and an inability to prevent undesirable or inappropriate actions. As inhibitory efficiency is a critical determinant of the contents of working memory (Hasher & Zacks, 1988; Stoltzfus et al., 1996; Zacks & Hasher, 1994), those tasks that rely on working memory--- including selective attention, reading and language comprehension, speech production, problem solving, and retrieval from memory—may all prove to be susceptible to synchrony effects. Furthermore, because inhibitory processing permits control over action by holding strong, well-practiced responses in abeyance until they can be checked for their appropriateness (e.g., Logan, 1994), heightened errors of action and an increase in the production of inappropriate responses (e.g., hyperverbosity; Arbuckle & Gold, 1993) can be expected at asynchronous times.

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