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A Deficit in Older Adults' Effortful Selection of Cued Responses

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ABSTRACT. J. J. Adam et al. (1998) provided evidence for an "age-related deficit in preparing 2 fingers on 2 hands, but not on 1 hand" (p. 870). Instead of having an anatomical basis, the deficit could result from the effortful processing required for individuals to select cued subsets of responses that do not coincide with left and right subgroups. The deficit also could involve either the ultimate benefit that can be attained or the time required to attain that benefit. The authors report 3 experiments (*N*s = 40, 48, and 32 participants, respectively) in which they tested those distinctions by using an overlapped hand placement (participants alternated the index and middle fingers of the hands), a normal hand placement, and longer precuing intervals than were used in previous studies. The older adults were able to achieve the full precuing benefit shown by younger adults but required longer to achieve the maximal benefit for most pairs of responses. The deficit did not depend on whether the responses were from different hands, suggesting that it lies primarily in the effortful processing required for those subsets of cued responses that are not selected easily.

Key words: aging, precuing, preparation, response selection

Older adults take longer than younger adults to respond in a variety of choice-reaction tasks (Proctor, Vu, & Pick, 2005). Although part of that longer response time (RT) is a result of decreased sensory and motor capabilities, the larger part is attributable to processes involved in selection of a response to a stimulus (Cerella, 1990). For example, Stelmach, Goggin, and Garcia-Colera (1987) stated, "Some of the relevant literature suggests that response selection processes may be the primary locus for much of the response slowing found in aging studies" (p. 39). Included in the literature to which they referred was the finding that when RT is partitioned into premotor and motor times (respectively, before or after activation of the forearm muscle for making a response), the longer RT of older adults in comparison with that of younger adults is localized primarily in the premotor time. Stelmach et al. noted that response selection and preparation in the elderly have been studied in only a limited amount of research. Although additional research on that topic has been conducted since 1987, it is still appropriate to characterize the amount of research on the topic as limited.

Sanders (1998), in his summary of the stage structure for choice reactions, listed response precuing as one of two variables whose primary effects are on the response-selection stage (the other being stimulus–response compatibility). Thus, one can study response selection by precuing different subsets of possible responses in advance of the imperative stimulus. Varying the subset of cued responses allows evaluation of whether responses are selected in the same qualitative manner by adults of different ages. Varying the interval between the precue and the imperative stimulus allows one to determine whether different amounts of time are required for older and younger adults to achieve the maximal benefit of the precued information.

Precuing Aimed Movements

Rosenbaum (1980) developed a commonly used version of the response-precuing task that involves aimed movements of the left or right arm. In the movement-precuing task, the participant places her or his left and right hands on home locations and, when an imperative stimulus is presented, moves one of the two hands to a response location. For each hand, two response locations are farther away from the participant's body in the horizontal plane than the home locations and two are closer. Precues can designate the hand, direction, or extent of the response that will ulti-

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mately be required. In Rosenbaum's study, precues were letter stimuli signaling hand (*L* for left or *R* for right), direction (*F* for forward or *B* for backward), and extent (*N* for near or *D* for distant), or any combination thereof. The imperative stimulus was a colored dot presented at the center of the screen that matched the color of a response location. Precuing any dimension reduced RT; the reduction was largest for hand, intermediate for direction, and least for extent. Also, the more dimensions that were precued, the more RT decreased. Rosenbaum interpreted his results as support for a model in which movement parameters are specified in a serial, fixed order (arm, direction, and extent).

Subsequent research indicated, though, that the major factor determining the precuing patterns is the ease with which the cued subset of responses can be selected (Goodman & Kelso, 1980; Larish & Frekany, 1985). Goodman and Kelso replicated Rosenbaum's (1980) method and found comparable results when they used similar stimuli. However, when Goodman and Kelso used a more compatible display consisting of eight lights arranged in the same configuration as the response locations, precuing was equally beneficial for all movement parameters. Thus, when spatially compatible precues are used, reducing possible differences in selecting the subsets of cued responses, there is no indication of fixed, serial specification of movement parameters. The differences in RT across precue conditions in Rosenbaum's original version of this task apparently reflected response-selection processes rather than motor-programming processes.

Using Goodman and Kelso's (1980) display, Stelmach et al. (1987; see also Stelmach, Goggin, & Amrhein, 1988) conducted a series of experiments to compare performance of older and younger adults on the movement-precuing task. Stelmach and colleagues used the two-limb, eight-choice, movement-precuing task just described. Although RT was longer for older than for younger adults, the older adults benefited at least as much as the younger adults from precues for all parameters (arm, direction, and extent), indicating that they could use the precue information to prepare any subset of responses. Similar results were obtained in studies of a two-choice task in which aimed movements of the right hand were made in left or right directions (Larish & Stelmach, 1982) and a four-choice task in which arm and extent varied (Chua, Pollock, Elliott, Swanson, & Carnahan, 1995). Thus, those investigators found no deficiency in the level of preparation for a subset of aimed movements that older adults can achieve, although some evidence indicated that older adults need more time to attain that level (e.g., Amrhein, Stelmach, & Goggin, 1991).

Precuing Discrete Key Presses

In another widely investigated variation of the response-precuing task, discrete key presses are used instead of aimed movements (Miller, 1982). The typical procedure for that key-press precuing task involves four stimuli and responses; the responses are made by the index and middle fingers of the left and right hands (see Figure 1, top half). A row of four plus signs is presented as a warning, followed shortly thereafter by two or four plus signs presented as precues in a row immediately below the warning row. After a variable interval, a single plus sign appears below one of the precued locations, and the participant is to respond by pressing the corresponding response key as quickly as possible. Miller used precuing intervals of up to 1 s and found

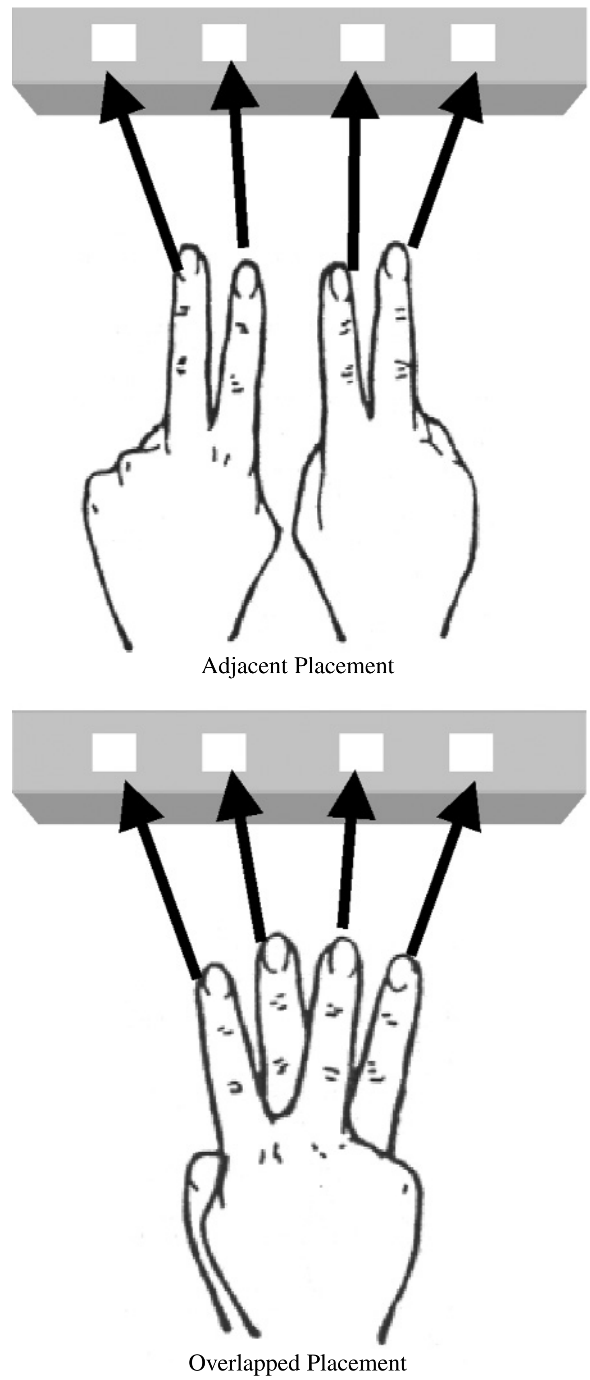

FIGURE 1. Illustration of the mapping of response keys to fingers for the adjacent and overlapped hand placements.

a benefit for precuing two responses only when the responses were on the same hand. He called that phenomenon the *same-hand advantage* and interpreted it as a reflection of a property of the motor system in which preparation of two response fingers is more effective when they are on the same hand rather than different hands.

However, Reeve and Proctor (1984) extended the precuing interval to 3 s and found that all precue conditions showed similar benefits at that interval compared with the effect of the uninformative precue of all four locations, demonstrating that the hand does not have to be specified before the finger. When averaged across intervals, precuing was most beneficial for two fingers on the same hand, intermediate for the same finger on each hand, and least beneficial for different fingers on different hands because of differences in the amount of time required for participants to obtain the maximal precuing benefit. Reeve and Proctor also had some participants perform with an overlapped hand placement for which the left-to-right ordering of fingers was right index, left middle, right middle, and left index (see bottom half of Figure 1). Although RT was longer with the overlapped placement than with the adjacent placement, the pattern of precuing benefits with respect to the cued locations was similar: Averaged across precuing intervals, RTs were shortest for cues that signaled the two left or two right locations, intermediate for those that signaled the two inner or two outer locations, and longest for those that signaled either pair of alternating locations. That pattern of results implies that the apparent advantage for precuing responses on the same hand is primarily one for precuing the two leftmost or two rightmost positions.

Reeve and Proctor (1984, 1990) provided considerable evidence that the precuing advantage for the left and right pairs of locations is the result of the salience of the left–right spatial distinction for both the stimulus and the response sets. That is, the linear arrays group easily into two left and two right locations. Because of the salience of the left–right distinction, participants can determine and prepare the subset of cued responses much quicker for those pairs of locations than for the less salient pairs. Consistent with that view, Reeve, Proctor, Weeks, and Dornier (1992) showed that by manipulating the grouping of the locations in the two arrays through spatial proximity, the pattern of precuing benefits could be altered to favor the salient subgroups.

Adam, Hommel, and Umiltà (2003) proposed a grouping model to account for the key-press precuing effects that is an elaboration of Reeve and Proctor's (1984, 1990) explanation. Adam and colleagues' model is based on the idea that automatic selection of the precued responses is possible if the precue is a salient subset of stimuli that corresponds with a salient subset of responses, but effortful, intentional selection is otherwise required. According to their model, a visual buffer and a motor buffer are created on every trial. The stimulus and response sets are organized in the respective buffers in salient subgroups on the basis of Gestalt organizational principles. For the four-choice, key-press precuing task, the groupings are of the two left and the two right stimulus and response locations (see Adam et al., Figure 2). Consequently, left–right precues consistent with that grouping allow automatic selection of the precued responses, whereas inner–outer or alternate location precues inconsistent with the grouping require an effortful reorganization of the response buffer so that it conforms to the visual buffer.

Adam et al. (1998) studied aging effects in the key-press precuing task in two experiments, and they concluded that, in contrast to the studies in which aimed movements were precued, their results showed "a substantial age-related deficit in preparing two fingers on different hands" (p. 881). Their Experiment 1 included only an uninformative-cue condition in which plus signs occurred in all four positions and a "hand cued" condition in which the two leftmost or two rightmost positions were cued. The precue appeared 100 ms before onset of the target stimulus in one block of trials and 2 s before in another, and all participants performed with a normal hand placement. Six age groups were tested; the mean ages of participants in each group were 25, 35, 45, 55, 65, and 75 years, respectively. As is commonly found, mean RT increased as age increased. Two other outcomes were of most importance. First, the precuing benefit for the hand-cued condition relative to that of the uninformative condition did not vary as a function of age: Older adults showed precuing benefits as large as those shown by younger adults. Second, an analysis of RT as a function of stimulus–response position indicated that, although younger adults showed similar RTs for the inner and outer positions, older age groups showed increasingly bow-shaped curves. For older adults, RT to the inner positions was slowed relatively more than was that to the outer positions. The bow-shaped pattern was particularly pronounced with the uninformative cues.

In Experiment 2, Adam et al. (1998) examined only two age groups (mean ages = 24 and 71 years). Moreover, they included two remaining precue conditions (the finger-cued condition in which the index or middle finger was cued and the neither-cued condition in which the index finger of one hand and the middle finger of the other were cued) and examined five precuing intervals (100, 500, 1,000, 1,500, and 2,000 ms) in distinct blocks. Averaged across intervals, the younger adults showed the typical pattern of differential precuing benefits: The benefit was largest for the hand-cued condition, intermediate for the finger-cued condition, and least for the neither-cued condition, with RT being shorter for all three of those conditions than for the uninformative condition. In contrast, the older adults showed a precuing benefit only for the hand-cued condition. For both age groups, the hand-cued condition had an advantage over the other informative precue conditions at the shortest interval. But, whereas the younger adults showed the typical pattern of benefits appearing for the other conditions at longer intervals, the older adults did not. Consequently, for the older adults, "only RTs in the hand-cued condition (567 ms) were significantly shorter than those in the uncued condition (629 ms), with RTs in the finger-cued, neither-cued, and uncued conditions not being significantly different (620, 623, and 629 ms, respectively; $p > .4$)" (Adam et al., p. 876). Also, the bow-shaped position pattern was again evident in the data for the older but not the younger adults. As summarized in their Abstract, Adam et al. concluded that their experiments showed "a substantial age-related deficit in preparing 2 fingers on 2 hands, but not on 1 hand" (p. 870) and that "advancing age increasingly slows reaction time more to the inner than to the outer stimulus-response positions" (p. 870).

Purpose

The conclusion of Adam et al. (1998) that older adults have a substantial deficit in preparing responses on different hands differs from the conclusion that other researchers have reached from the movement-precuing studies; in those investigations, older adults have been shown to benefit from precuing movement direction and extent when hand remains uncertain (e.g., Stelmach et al., 1987). The possibility exists that distinct processes are involved in preparing aimed movement and key-press responses (e.g., Adam & Pratt, 2004) and that those processes are differentially affected by age. However, the conclusion of Adam et al. that there is an age-related deficit in preparing fingers on different hands also does not conform to the results obtained with younger adults for the key-press precuing task; according to those results, the precuing advantage has been shown to be mainly for the two leftmost or two rightmost locations and not for the left or right hand (Reeve & Proctor, 1984). Nor is it in agreement with Adam et al.'s (2003) more recent emphasis on spatial subgroups as the primary determinant of the pattern of differential precuing benefits for young adults.[1]

To determine whether the precuing deficit for older adults demonstrated by Adam et al. (1998) reflects an impaired ability to prepare fingers on different hands or to engage in the effortful processes required to use the inner–outer and alternate location precues, one must include an overlapped hand placement similar to that used by Reeve and Proctor (1984). If the deficit follows the hand distinction, then the hypothesis that older adults are deficient in preparing two fingers on different hands will be supported. If the deficit follows the spatial locations, then the implication will be that the deficiency is in selection of the subsets of cued responses that require effortful processing. Such a finding would imply that the age-related precuing deficit is mainly a consequence of a general loss of efficiency in executive functioning evident in other tasks (e.g., Span, Ridderinkhof, & van der Molen, 2004). The present Experiment 1 was thus a replication of Experiment 2 of Adam et al. (with minor differences in method) that included all precue conditions and had participants perform with a normal, adjacent hand placement or an overlapped hand placement.

Regardless of whether the precuing deficit for older adults observed in Experiment 2 of Adam et al. (1998) was for fingers on different hands or for different spatial precue pairs, the deficit may reflect an older individual's need for more time to select and prepare the cued responses rather than the final level of preparation that he or she can achieve. Adam et al. noted that a three-way interaction of age with preparation interval and precue type in their data qualified their statements about an age-related precuing deficit "somewhat by indicating that older participants were indeed able to reduce RT in the finger-cued and neither-cued conditions but only with the longest preparation intervals of 1,500 ms and 2,000 ms . . . and only to a modest extent" (p. 876). They downplayed that interaction, however, stating, "Older participants were only marginally able to reduce RT in the finger-cued and neither-cued conditions. Also, these conditions showed the largest error rates" (p. 877). In the General Discussion, after acknowledging the possibility that 2 s may not have been enough time for older adults to prepare the cued responses in all precue conditions, Adam et al. dismissed that possibility as implausible, stating,

> It could be argued that, at least in principle, preparation intervals longer than 2 s would allow older participants to show the same precuing benefits as those of younger participants. This possibility is not particularly plausible, however, because in Experiment 2 older participants more than younger participants were negatively affected by increasing the duration of the preparation interval. (p. 880)

Yet, Reeve and Proctor (1984) found that younger adults needed 3 s to show a complete precuing benefit for the finger-cued (i.e., inner–outer) and neither-cued (i.e., alternate locations) conditions when the precue interval varied randomly between 0 and 3 s. It seems reasonable, therefore, to think that older adults would require even more time than younger adults to select and prepare precued responses, especially if the responses are for pairs that require more effort to process.

We designed Experiments 2 and 3 to test whether any decrement in precuing benefits for older adults reflects a longer time to attain the maximum benefits for some precue combinations or a deficit in the ultimate level of preparation that can be achieved. Experiment 2 was similar to Experiment 1, but with the precuing intervals extended to 3, 4, and 5 s. In Experiment 3, we used a range of intervals from Experiments 1 and 2, but with the intervals randomly mixed rather than blocked. That experiment allowed us to determine whether older adults can use precues as effectively as younger adults when there is uncertainty about the time available for preparing the cued responses.

EXPERIMENT 1

Experiment 1 was a replication of Experiment 2 of Adam et al. (1998), in which we used all precue conditions at blocked intervals of 100, 500, 1,000, 1,500, and 2,000 ms, with two changes of note. First, the stimulus and response locations were equally spaced, rather than separated into left and right pairs by a large space. Explicitly grouping the locations by spatial proximity into left and right pairs, as Adam et al. did, introduces a possible advantage for precuing the two left and two right locations (which, in their study, was the hand-cued condition) because they are within physically distinct groups, whereas the other pairings are not (Reeve et al., 1992). The other change was to include a condition in which participants responded with the overlapped hand placement, as well as one in which they used a normal hand placement. If older adults are deficient at preparing responses on different hands, then with the overlapped placement a benefit should be evident primarily for the alternate-location precues for which the responses involve fingers on the same hand. In contrast, if older adults are deficient at effortful selection of cued responses that do not conform to the natural stimulus and response subgroups, then with the overlapped placement a benefit should be evident primarily for the left–right precues, even though they involve responses on different hands.

Method

Participants

Twenty younger adults (M = 19.60 years, SD = 1.45 years; 10 women and 10 men) and 20 older adults (M = 65.3 years, SD = 6.98 years; 14 women and 6 men) were tested. The younger adults were undergraduates at Purdue University, and the older adults were recruited from Purdue University, Purdue University Calumet, and surrounding communities. All had at least a high school education, were in good health, and reported no visual or hearing deficit beyond any correctable with glasses or hearing aids. They were high functioning, able to drive and participate in their communities. The undergraduates received experimental credit toward their psychology course requirements, and the older adults were paid $10 for their participation.

Apparatus and Stimuli

Stimuli were presented on personal computers, with 14-in. VGA color monitors. We used Micro Experimental Laboratory (MEL Version 2.01) to program the experiment. The participant sat directly in front of the monitor, at a viewing distance of approximately 60 cm. All stimuli were white on a black background. The warning signal was four filled plus signs (0.8 cm × 0.8 cm; 0.76° × 0.76°) separated by 3.5 cm (3.33°). The precue was presented in a row located 1 cm (0.95°) below the warning sign, and also consisted of plus signs of the same size (see Figure 2). For the uninformative condition, the precue was four plus signs presented directly beneath the warning plus signs; for the left–right precue condition, two plus signs appeared directly below the warning sign in the two leftmost or two rightmost positions; for the alternate precue condition, two plus signs appeared directly below the second and fourth warning plus signs or below the first and third signs; for the inner–outer precue condition, two plus signs appeared directly below the inner warning plus signs or the two outer ones. The imperative stimulus was a single plus sign of the same size as the warning and precue plus signs that appeared 1 cm (0.95°) below one of the precue stimuli. The plus signs (and thus the size of the entire array) were considerably larger than those typically used (e.g., Reeve & Proctor, 1984, 3 mm square; Adam et al., 1998, 2.5 mm wide and 4.5 mm high), which enabled us to ensure that the older adults had no difficulty seeing them. Participants made responses by pressing one of four equally spaced keys (Keys 1, 2, 3, and 4, from left to right) of a 5-key MEL response box.

Procedure

Half the participants in each age group performed by using an adjacent hand placement (see top half of Figure 1), for which they placed the middle and index fingers from each hand on the response keys. The other half used an overlapped hand placement (see bottom half of Figure 1), for which they placed the right hand over the left hand and alternated the index and middle fingers from each hand on the response keys. Participants were tested individually in a single session, and the experimenter stayed in the room throughout the session to ensure that the appropriate hand placement was maintained. Participants were instructed to respond as quickly as possible to the final plus sign, without making many errors. They were also told that the precue was always valid and that they were to try to use it "to narrow down the possible choices."

On each trial, the warning signs were presented, and, after 500 ms, the precue signs appeared. The imperative stimulus was presented after the specified precue interval. All stimuli (warning, precue, and imperative) remained on the screen until a response was made. We measured RT from onset of the imperative stimulus to the depression of a response key. The intertrial interval was 1 s. We blocked the precue intervals at 100, 500, 1,000, 1,500, and 2,000 ms. Each block consisted of 96 trials, 16 practice trials, and 80 test trials, and the order of the blocks (and precue intervals) was counterbalanced between participants. Within each block, we presented each precue type equally often in a random order. Participants received an error tone of 500 ms on incorrect trials before the intertrial interval.

Results

We excluded RTs under 200 ms (anticipations) and greater than 2,000 ms and the practice trials from the analyses (less than 2% of all trials) for all experiments. We computed and submitted mean correct RT and percentage error (PE) for each participant in separate 4 (precue type: uninformative, left–right, alternate, and inner–outer) × 5 (precue interval: 100, 500, 1,000, 1,500, and 2,000 ms) × 4 (stimulus–response position: 1, 2, 3, and 4, in left to right order) × 2 (age: younger or older adults) × 2 (hand placement: adjacent or overlapped) analyses of variance (ANOVAs). The latter two

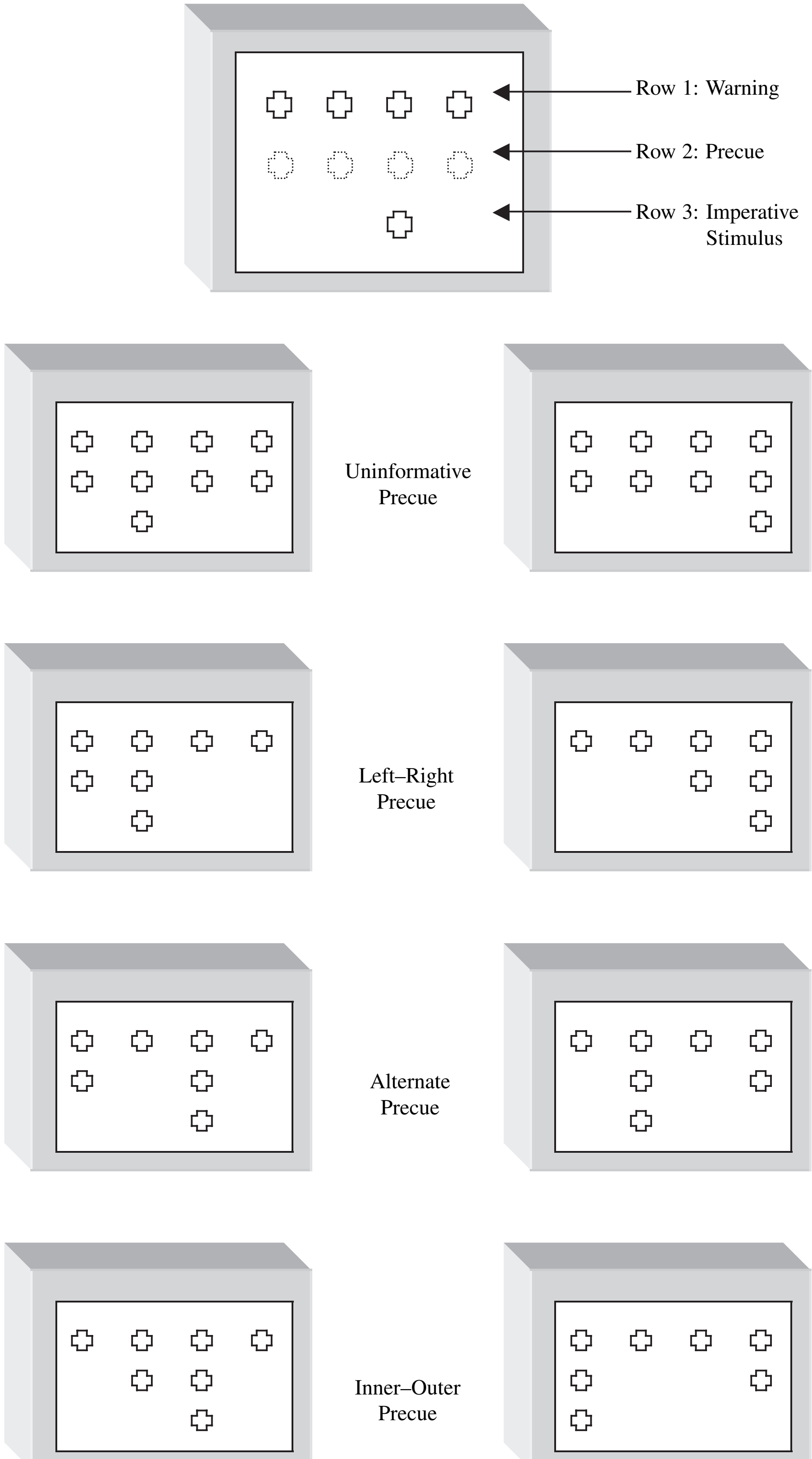

FIGURE 2. Illustration of the stimulus displays for the different precue conditions.

variables were between-participants (see Table 1 and Figures 3 and 4). The *F* ratios for any terms in the ANOVAs that are not reported were not statistically significant at the .05 α level.

Reaction Time

Responses were slower for older (M = 682 ms) than for younger (M = 488 ms) adults, $F(1, 36) = 31.02$, mean square error (*MSE*) = 976,532, $p < .001$, and for overlapped (M = 655 ms) than for adjacent (M = 514 ms) hand placement, $F(1, 36) = 16.40$, *MSE* = 976,532, $p < .001$ (see Table 1). Those two variables did not interact, $F < 1.0$.

The main effect of precue type was significant, $F(3, 108) = 12.88$, *MSE* = 14,160, $p < .001$. Mean RT was longest for the uninformative cue (M = 603 ms), shortest for the left–right cues (M = 566 ms), and intermediate for the alternate (M = 587 ms) and inner–outer (M = 581 ms) cues. Precue type interacted with hand placement, $F(3, 108) = 3.42$, $p = .020$, and with age, $F(3, 108) = 2.82$, $p = .042$. Follow-up analyses indicated that the interaction with hand placement involved two components. First, the benefit for the informative cues relative to the uninformative cue tended to be larger with the adjacent (mean difference [*MD*] = 35 ms) than with the overlapped (*MD* = 14 ms) placement, $F(1, 36) = 3.79$, $p = .059$. Second, the left–right cues showed a larger advantage over the other two informative precue types with the adjacent (*MD* = 28 ms) than with the overlapped (*MD* = 8 ms) placement, $F(2, 72) = 3.24$, $p = .045$. The interaction with age resulted primarily from the benefit for the three informative precue types in comparison with the larger benefit of uninformative cue for the younger (*MD* = 36 ms) than for the older (*MD* = 13 ms) adults, $F(1, 36) = 5.13$, $p = .030$.

The three-way interaction of precue type with hand placement and age was not significant, $F(3, 108) = 1.164$, $p = .327$, but separate ANOVAs for the older and younger adults indicated a significant interaction of precue type with hand placement for the older, $F(1, 54) = 3.08$, $p = .035$, but not the younger, $F(1, 54) = 1.28$, $p = .29$, adults. Averaged across precue intervals, the younger adults showed the typical finding that the relative precuing benefits did not depend on the hand placement. In contrast, the older adults showed a 28-ms benefit for the informative precues with the adjacent placement, but no benefit with the overlapped placement (see Figure 3).

There was no main effect of precue interval, $F < 1.0$, but precue interval interacted with age, $F(4, 144) = 2.78$, *MSE* = 79,786, $p = .033$, and precue type, $F(12, 432) = 3.79$, *MSE* = 6,419, $p < .001$. RT tended to decrease as the interval

TABLE 1. Mean Reaction Time and Percentage Error for the Adjacent and Overlapped Hand Placements in Experiment 1 as a Function of Precue Type, Precue Interval, and Age Group

	Precue interval									
	100 ms		500 ms		1,000 ms		1,500 ms		2,000 ms	
Precue type	RT	%	RT	%	RT	%	RT	%	RT	%
Adjacent placement: younger adults										
Uninformative	445	1.50	429	1.50	457	0.50	465	1.00	442	0.50
Left–Right	411	1.00	395	0.50	392	1.00	398	0.50	371	1.00
Alternate	434	3.00	433	4.00	430	2.50	407	0.50	383	1.00
Inner–Outer	418	1.00	419	3.00	409	1.50	399	2.50	391	2.00
Adjacent placement: older adults										
Uninformative	575	0.50	614	1.00	625	1.50	674	1.00	670	0.00
Left–Right	557	1.50	585	0.50	582	0.50	587	0.00	584	0.50
Alternate	602	1.00	647	2.50	621	2.50	644	2.00	618	2.50
Inner–Outer	579	1.00	594	2.00	616	2.50	622	1.00	625	0.00
Overlapped placement: younger adults										
Uninformative	568	3.00	596	2.50	575	1.00	567	1.00	599	1.00
Left–Right	561	3.00	563	3.05	533	2.50	530	1.50	525	2.50
Alternate	569	5.13	577	0.50	544	2.00	518	3.00	523	4.50
Inner–Outer	569	3.50	590	4.50	557	3.00	541	2.00	557	3.00
Overlapped placement: older adults										
Uninformative	728	6.00	709	5.50	734	0.00	756	1.00	831	0.50
Left–Right	745	7.50	699	4.50	724	2.50	757	6.00	832	3.50
Alternate	744	8.00	748	4.96	755	4.00	741	4.00	812	6.00
Inner–Outer	740	4.00	696	3.00	728	4.00	761	3.50	810	3.50

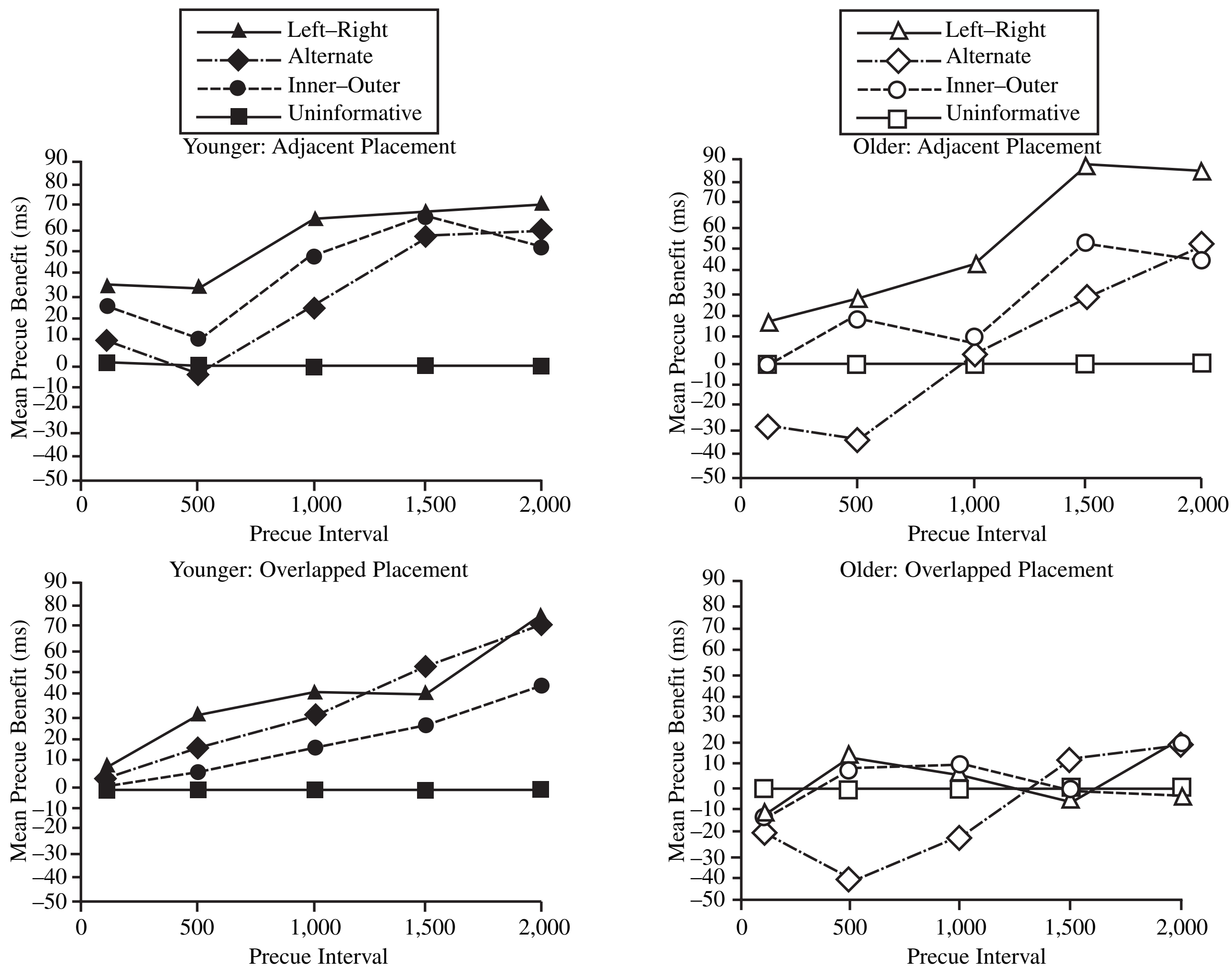

FIGURE 3. Mean precuing benefits (reaction time [RT] for each precue type minus RT for the uninformative precue) for the adjacent and overlapped hand placements in Experiment 1 as a function of age group and precue interval (ms).

increased for the younger adults but to increase for the older adults (see Table 1). The magnitude of the increase for our older adults, who were, on average, 65 years old, was similar to that of the older adults in Adam et al. (1998), who were, on average, 71 years old, indicating a similar level of functioning. For the uninformative cue, RT increased from 579 ms at the shortest interval to 635 ms at the longest interval; for the informative precue types, the functions were much flatter.

The main effect of stimulus–response position was significant, $F(3, 108) = 41.90$, $MSE = 55{,}791$, $p < .001$. As shown in Figure 4, that effect was caused primarily by the 93-ms slower responses for the middle two positions than for the outer two positions. The only remaining significant effects were the two-way interactions of position with hand placement, $F(3, 108) = 4.52$, $p = .008$, and position with age, $F(3, 108) = 5.47$, $p = .003$. The difference between the two inner and two outer positions was larger with the overlapped hand placement ($MD = 120$ ms) than with the adjacent one ($MD = 67$ ms) and for older adults ($MD = 127$ ms) than for younger adults ($MD = 60$ ms). The latter finding is consistent with that reported by Adam et al. (1998).

Percentage Error

The percentage error (PE) data showed a main effect of hand placement, $F(1, 36) = 10.84$, $MSE = 295.74$, $p = .002$; PE was higher for the overlapped placement ($M = 3.35\%$) than for the adjacent placement ($M = 1.35\%$). The main effect of age was not significant, nor did age interact with hand placement.

There was a main effect of precue type, $F(3, 108) = 7.65$, $MSE = 49.85$, $p < .001$. PE was 1.53% for the uninformative cue, 2.18% for the left–right cues, 2.52% for the inner–outer cues, and 3.18% for the alternate cues. That pattern is similar to the one reported by Adam et al. (1998), who used only the adjacent placement, for which the most errors were made with the inner–outer and alternate cues. The main effect of precue interval was also significant, $F(4, 144) = 3.09$, $MSE = 65.29$, $p = .029$; PE was higher at the

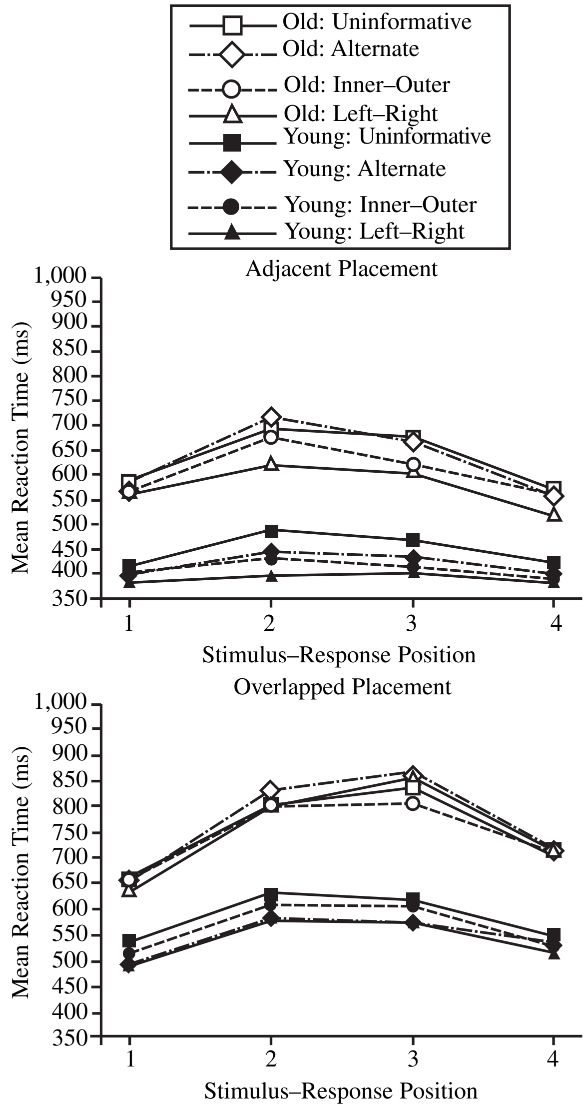

FIGURE 4. Mean reaction time for the adjacent and overlapped hand placements in Experiment 1 as a function of age group, precue type, and stimulus–response position.

two shortest intervals (M = 2.93%) than at the three longer ones (M = 1.96%). Precue interval interacted with hand placement, $F(4, 144) = 2.77$, $p = .044$; the elevation in PE at the two shortest intervals was more pronounced for the overlapped placement (MD = 1.56%) than for the adjacent placement (MD = 0.40%).

The main effect of stimulus–response position was significant, $F(3, 108) = 22.41$, $MSE = 109.92$, $p < .001$, as was the two-way interaction of position with hand placement, $F(3, 108) = 3.38$, $p = .033$. The error rate was higher for the two inner stimulus–response positions (M = 3.9%) than for the outer two positions (M = 0.8%). This difference between the two inner and two outer positions was larger with the overlapped hand placement (MD = 4.2%) than with the adjacent one (MD = 1.8%).

Discussion

With the adjacent hand placement, our results were comparable with those of Adam et al. (1998). For younger adults, the benefit for the informative precue types increased over the shorter intervals, reaching a level of roughly equivalent benefits for all three types at the two longest precuing intervals. For older adults, the left–right cues showed a larger benefit than the alternate and inner–outer cues at all intervals, although those latter two precue types started to show significant benefits at the 1,500- and 2,000-ms intervals (ps < .05), as in Adam et al.'s study. Thus, our older adults averaging 65 years of age yielded results similar to those of Adam et al.'s older adults, who averaged 71 years. Moreover, our results demonstrated that the age-related precuing deficit noted by Adam et al. occurs even when the two left and two right stimulus and response positions are not physically separated into two subgroups by a large space between them.

With the overlapped hand placement, the younger adults showed a typical pattern of numerically larger precuing benefits overall for the left–right precues than for the other informative precue types, even though the two cued responses for that condition were on different hands. At the two longest intervals, the alternate location cues (within-hand locations) and the left–right cues (between-hands locations) showed large benefits of roughly similar magnitude compared with that of the uninformative cue. In contrast, the older adults who performed with the overlapped placement showed essentially no benefit for any of the informative precue types compared with that of the uninformative cue at any interval. Thus, for the intervals ranging from 100 to 2,000 ms examined in the present experiment, older adults who performed with the more awkward overlapped hand placement showed little benefit from precues specifying two responses, regardless of whether the responses involved fingers within a single hand (the alternate location cues) or on different hands.

This absence of a precuing benefit for the older adults with the overlapped hand placement could be interpreted as indicating that the instructions did not sufficiently stress use of the precue information. However, at least two aspects of the data suggest that this was not the case. First, as noted earlier, the older adults showed precuing benefits for the adjacent hand placement when given the same task instructions. Second, the younger adults showed precuing benefits for the overlapped placement as well as for the adjacent placement. Thus, the absence of precuing benefit for older adults likely was a consequence of the overloading of participants' reduced processing capacities by the high processing demands required for them to use the cues with the overlapped placement.

We also replicated the finding of Adam et al. (1998) that RT was an inverted U-shaped function of stimulus–response position. That pattern was larger for the older adults than for the younger adults, as in the study of Adam et al., and was more pronounced with the overlapped placement.

EXPERIMENT 2

Regardless of whether the precuing deficit for older adults has an anatomical or spatial basis, the deficit could occur because older adults need more time than younger adults to select and prepare the two cued responses for the more difficult precue conditions and not because they are unable to prepare some subsets of responses. The longest precuing interval examined by Adam et al. (1998) and in our Experiment 1 was 2 s, which is shorter than the 3-s interval that Reeve and Proctor (1984) found necessary for younger adults to show equivalent benefits across the three informative precue types in several experiments. In the present Experiment 2, therefore, we eliminated the four shortest precuing intervals and extended the range to include longer intervals of 3, 4, and 5 s. Those changes allowed us to determine whether, if given sufficient time, older adults can show benefits of similar magnitude for all of the informative precue types.

Method

Forty-eight new volunteers with the same characteristics as those in Experiment 1 participated: 24 younger adults (*M* = 20.6 years, *SD* = 1.75 years; 12 women and 12 men) and 24 older adults (*M* = 65.6 years, *SD* = 5.20; 11 women and 13 men). For each age group, 12 participants performed with the adjacent hand placement and 12 with the overlapped placement. The apparatus, stimuli, and procedure were identical to those used in Experiment 1, except that participants performed four blocks of trials with the precue intervals of 2, 3, 4, and 5 s.

Results

Similar to Experiment 1, we computed and submitted mean RT and PE for each participant to separate ANOVAs (see Table 2 and Figures 5 and 6).

Reaction Time

Responses were slower for older adults (*M* = 674 ms) than younger adults (*M* = 493 ms), $F(1, 44) = 30.74$, $MSE = 824{,}300$, $p < .001$, and for the overlapped placement (*M* = 647 ms) than the adjacent placement (*M* = 521 ms), $F(1, 44) = 14.74$, $p < .001$. Older adults' responses tended to be slowed more than younger adults' for the overlapped placement compared with their times for the adjacent placement

TABLE 2. Mean Reaction Time and Percentage Error for the Adjacent and Overlapped Hand Placements in Experiment 2 as a Function of Precue Type, Precue Interval, and Age Group

	Precue interval							
	2,000 ms		3,000 ms		4,000 ms		5,000 ms	
Precue type	RT	%	RT	%	RT	%	RT	%
Adjacent placement: younger adults								
Uninformative	509	1.25	482	0.83	509	2.50	525	3.75
Left–Right	437	1.25	432	1.67	430	0.42	444	0.42
Alternate	450	1.25	433	0.00	454	1.25	434	0.83
Inner–Outer	454	2.36	454	1.67	461	1.25	430	1.67
Adjacent placement: older adults								
Uninformative	624	3.33	632	1.25	674	1.67	704	1.67
Left–Right	487	1.67	511	2.92	539	2.08	582	0.00
Alternate	562	2.08	554	2.08	580	3.33	629	3.33
Inner–Outer	516	2.08	537	0.42	584	0.00	610	1.25
Overlapped placement: younger adults								
Uninformative	588	2.50	548	1.25	590	2.50	617	4.17
Left–Right	514	4.58	484	0.42	502	3.33	527	1.25
Alternate	491	3.75	488	1.67	485	1.25	521	2.08
Inner–Outer	525	1.35	510	1.25	517	0.42	528	2.08
Overlapped placement: older adults								
Uninformative	860	3.44	911	2.50	935	1.94	926	3.85
Left–Right	755	2.08	686	6.35	715	2.08	715	1.35
Alternate	792	6.25	699	3.02	734	0.94	669	4.67
Inner–Outer	741	5.52	694	3.02	705	3.61	717	1.67

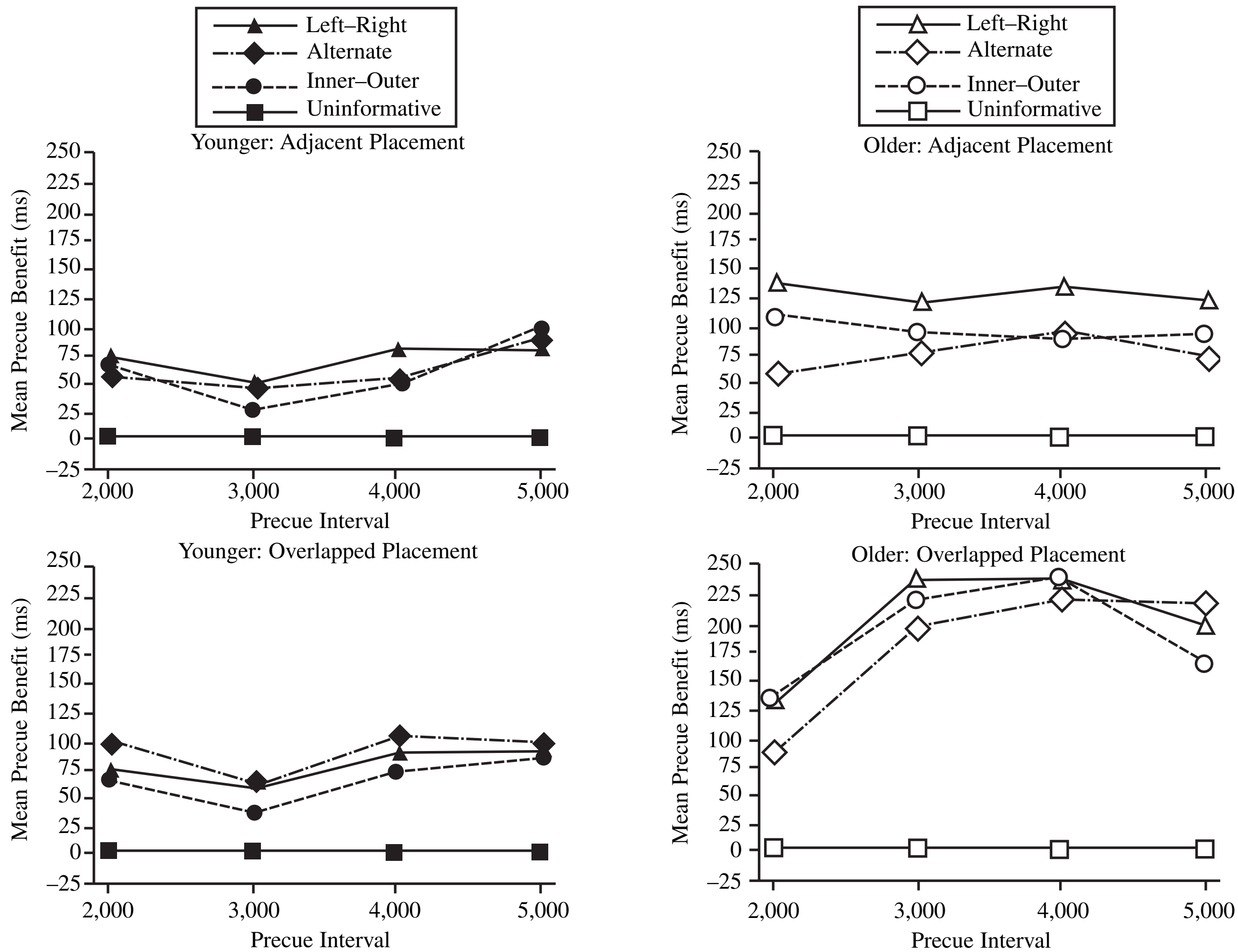

FIGURE 5. Mean precuing benefits (reaction time [RT] for each precue type minus RT for the uninformative precue) for the adjacent and overlapped hand placements in Experiment 2 as a function of age group and precue interval.

(*MD*s = 183 ms vs. 69 ms), but the interaction of age and hand placement was not significant, $F(1, 44) = 3.06$, $p = .087$.

The main effect of precue type was significant, $F(3, 132) = 71.33$, $MSE = 31{,}850$, $p < .001$. Mean RT was longer for the uninformative cue ($M = 665$ ms) than for the informative precue types, which differed only slightly (left–right, $M = 548$ ms; alternate, $M = 561$ ms; inner–outer, $M = 562$ ms). The relative absence of differences between the three informative precue types is to be expected because we used only long intervals in this experiment. Precue type interacted with hand placement, $F(3, 132) = 4.99$, $p = .003$. Follow-up analyses indicated that that interaction resulted primarily from the larger precuing benefit for the informative precues for the overlapped placement ($MD = 134$ ms) than for the adjacent placement ($MD = 83$ ms), $F(1, 46) = 4.84$, $p < .035$. Precue type also interacted with age, $F(3, 132) = 9.66$, $p < .001$. In contrast to Experiment 1, the comparative benefit for the three informative precue types over that of the uninformative cue was larger for the older adults ($MD = 146$ ms) than for the younger adults ($MD = 71$ ms; see Figure 5). For the informative precues, RT showed a tendency to be shorter for the left–right cues than for the other two precue types, $F(2, 88) = 3.02$, $p = .054$; the benefit was larger for the older adults ($MD = 21$ ms) than for the younger adults ($MD = 6$ ms), $F(2, 88) = 3.37$, $p = .039$. Most important for the present concerns, the informative precue types showed no three-way interaction of precue type and age with hand placement, $F < 1.0$, and when the data for the older adults alone were analyzed, no Precue Type × Hand Placement interaction was found, $F(2, 44) = 1.94$, $p = .156$. Thus, those analyses showed little evidence of an age-related deficit in preparing responses on two hands as opposed to one.

The main effect of precue interval was not significant, $F(3, 132) = 1.85$, $MSE = 78{,}747$, $p = .14$, although RT tended to be shorter at the two shortest intervals ($M = 574$ ms) than at the two longest ones ($M = 594$ ms). Precue interval did not interact with age, $F < 1.0$, but did interact with precue type, $F(9, 396) = 2.80$, $MSE = 8{,}129$, $p = .003$. However, that inter-

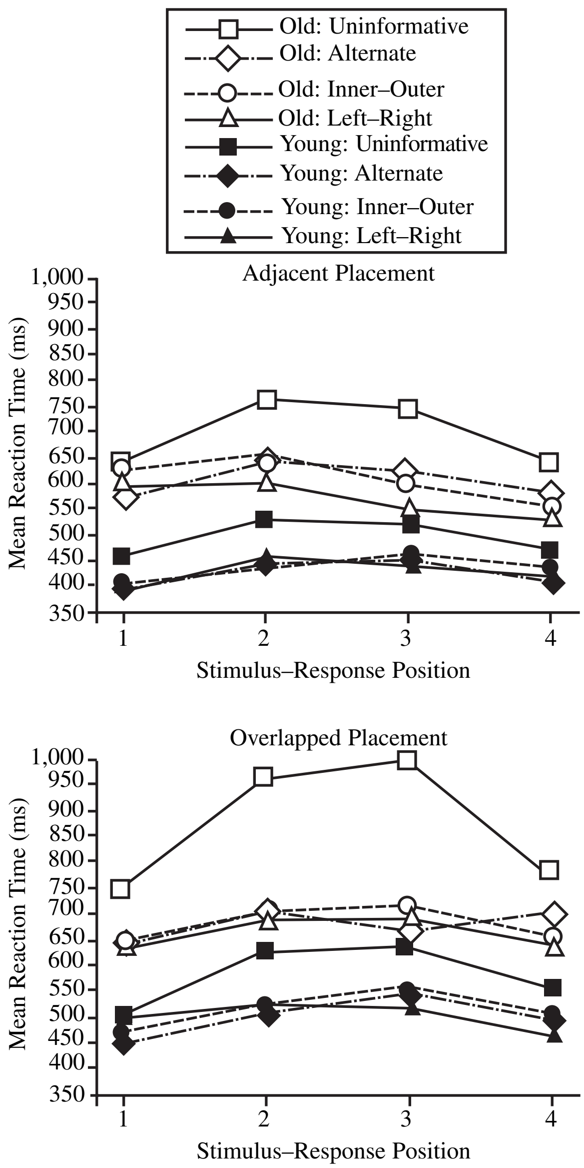

FIGURE 6. Mean reaction time for the adjacent and overlapped hand placements in Experiment 2 as a function of age group, precue type, and stimulus–response position.

action was qualified by a three-way interaction of precue type, precue interval, and age, as well as a four-way interaction of those variables with hand placement, *F*s(9, 396) = 2.89 and 2.44, *MSE* = 8,129, *p*s = .003 and .010. Examination of Figure 5 indicates that the younger adults showed similar benefits for all informative precue types across the range of intervals. For the older adults, comparison of the informative precue types with the uninformative cue showed a three-way interaction with hand placement and precuing interval, *F*(3, 66) = 5.85, $p < .001$: For the adjacent placement, the precuing benefit did not interact with interval, $F < 1.0$, but for the overlapped placement, the precuing benefit was smaller at the 2-s interval than at the longer ones, *F*(3, 33) = 7.05, $p <$ .001. Thus, the older adults apparently needed a longer time to achieve maximal preparation of the precued subset of responses with the more difficult overlapped hand placement.

The main effect of stimulus–response position was significant, *F*(3, 132) = 31.35, *MSE* = 42,763, $p < .001$. As in Experiment 1, that effect resulted primarily from the longer RT for the middle two positions (*M* = 620 ms) than for the outer two positions (*M* = 548 ms). The two-way interactions of position with precue type, *F*(9, 396) = 9.80, *MSE* = 11,956, $p < .001$, and with age, *F*(3, 132) = 3.91, *MSE* = 42,763, *p* = .010, were significant, as was the three-way interaction of those variables, *F*(9, 396) = 3.15, *MSE* = 11,956, $p < .001$. The former interaction reflected the larger difference in RT between the inner and outer positions for the uninformative condition than for the informative precue conditions, whereas the latter interaction indicated that that pattern was more evident for older than for younger adults (see Figure 6). The four-way interaction of Position × Precue Type × Precue Interval × Hand Placement also was significant, *F*(27, 1188) = 1.92, *MSE* = 7,265, *p* = .003, but because the effect accounted for little variance, we have not attempted to describe it.

Percentage Error

PE showed a main effect of hand placement, *F*(1, 44) = 6.03, *MSE* = 144.92, *p* = .018—it was higher for the overlapped placement (*M* = 2.68%) than for the adjacent placement (*M* = 1.61%)—and interval, *F*(3, 132) = 2.84, *MSE* = 55.87, *p* = .041. More errors were made at the shortest and longest intervals (*M* = 2.45%) than at the intermediate ones (*M* = 1.84%). Precue type and precue interval also interacted, *F*(9, 396) = 2.92, *MSE* = 37.20, *p* = .002.

The main effect of age was not significant, *F*(1, 44) = 3.17, *p* = .082, although older adults tended to make more errors (*M* = 2.53%) than younger adults (*M* = 1.76%). Age did not interact with hand placement, $F < 1.0$, but age entered into a three-way interaction with precue type and precue interval, *F*(9, 396) = 2.28, *MSE* = 37.20, *p* = .017. That interaction reflected in part the finding that the younger adults showed the largest differences in PE between precue conditions at the 2,000- and 5,000-ms intervals; PE was smaller for the uninformative and inner–outer cue types and larger for the left–right and alternate cue types at the first interval than at the last. In contrast, for older adults, the largest differences in PE were at the 3,000- and 5,000-ms intervals; the main feature of this pattern was that the left–right cues showed the largest error rate at the 3,000-ms interval but the smallest at the 5,000-ms interval. The four-way interaction of those variables with hand placement was also significant, *F*(9, 396) = 1.99, *MSE* = 37.20, *p* = .039. Older adults performing with the overlapped hand placement had particular difficulty at the short precue intervals for the informative precue conditions.

The main effect of stimulus–response position was significant, *F*(3, 132) = 18.53, *MSE* = 82.26, $p < .001$. As in Experiment 1, that position effect resulted from the higher

PE for the inner positions (*M* = 2.69%) than for the outer positions (*M* = 0.92%). Position also interacted with precue type, $F(9, 396) = 2.32$, $MSE = 61.00$, $p = .015$. The difference between the inner and outer positions was larger for the uninformative cue (*MD* = 3.45%) than for the informative cues (*MD* = 2.02%).

Discussion

For the longer precuing intervals used in this experiment, with the adjacent hand placement, both younger and older adults showed large benefits for all informative precue types. Thus, much as when they prepare aimed movement responses, when older adults are given sufficient time to prepare, they are able to obtain substantial benefits for all pairs of cued key-press responses, even when they involve fingers on different hands. Similar results were obtained with the overlapped placement; the older adults showed larger precuing benefits than the younger adults. Thus, in contrast to Experiment 1, in which the older adults showed little benefit from informative precues for the overlapped placement when the precuing interval ranged between 100 ms and 2 s, they showed substantial benefits when the interval ranged from 2 to 5 s. Those findings are generally consistent with the grouping model of Adam et al. (2003), which posits that it is possible to select and prepare less natural subgroups of precued responses but with more effort and longer time than for more natural subgroups.

When older adults performed with the adjacent placement, the benefits differed across the three precue types—they were 30 ms larger for the left–right cues than for the inner–outer cues, which in turn produced a benefit that was 19 ms larger than that for the alternate location cues. Thus, with an adjacent hand placement, older adults did not show as much benefit for the different-hand precues as for the same-hand precues, even at long precuing intervals. Note, however, that they did show substantial benefits for all informative precue types; the benefit for the worst, alternate cues relative to the uninformative cue (*MD* = 88 ms), was larger than the 49-ms difference between them and the left–right cue type. If that advantage for the left–right cues with the adjacent placement indicated a residual deficiency for older adults in preparing responses to the same level when they are on different hands, then the interaction of precue type and hand placement should have been significant for older adults, as should the three-way interaction of those variables with age for all of the participants. Yet, neither interaction approached significance. Note that for all except the 5-s precue interval, with the overlapped placement, older adults showed shorter mean RT for the left–right cues than for the alternate cues, for which the responses were on the same hand.

The shortest precuing interval of 2 s in this experiment was the same as the longest interval in Experiment 1. Whereas that 2-s trial block showed little evidence of precuing benefits in Experiment 1, it clearly did in Experiment 2, although the benefits were not as large as for intervals of 3 s or longer. Why was there little evidence of precuing benefits for the 2-s trial block in Experiment 1? A provisional answer to that question is that previous performance with shorter precuing intervals in Experiment 1 induced participants to adopt a strategy of not using the precue information in the 2-s interval trial block. Because the order of the precue-interval blocks was counterbalanced across participants, 2 of the 10 older adults in Experiment 1 who performed with the overlapped placement received the 2-s precuing interval first. Those 2 participants showed an average precuing benefit of 102 ms for the three informative cue conditions, which is comparable with the values of 97 ms for all participants in Experiment 2 and 121 ms for the 3 participants in that experiment who received the 2-s precuing interval first. The remaining 8 participants in Experiment 1, who performed one or more trial blocks with shorter intervals before performing the 2-s interval block, showed no precuing benefit in that block (*MD* = –6 ms).

The stimulus–response position effects were pronounced for older adults with the uninformative cue compared with that with the informative cues, particularly with the overlapped hand placement. Much of the larger precuing benefit shown by the older adults compared with that of the younger adults can be attributed to the lower RT cost for the inner positions with the informative precue types than with the uninformative one.

EXPERIMENT 3

In Experiments 1 and 2, we held the precuing interval constant within a trial block. However, a more typical procedure is to vary the interval randomly (e.g., Miller, 1982; Reeve & Proctor, 1984) so that participants are uncertain about how much time is available to prepare for the imperative stimulus. In Experiment 3, we used a range of intervals (three short and two long) from Experiments 1 and 2, with the intervals randomly intermixed.

Method

Thirty-two adults with the same traits as those in Experiments 1 and 2 participated: 16 younger adults (*M* = 19.75 years, *SD* = 1.18 years; 6 women and 10 men) and 16 older adults (*M* = 63.25 years, *SD* = 8.37 years; 10 women and 6 men), half of whom performed with the adjacent hand placement and half with the overlapped placement. The apparatus, stimuli, and procedure were identical to that in Experiment 1, except that participants performed five blocks of 96 trials, each of which contained precue intervals of 100, 500, 1,000, 2,000, and 5,000 ms, randomly intermixed.

Results

We computed and submitted mean RT and PE for each participant to separate 4 (precue type: no cue, left–right, alternate, and inner–outer) × 5 (precue interval: 100 ms, 500 ms, 1 s, 2 s, or 5 s) × 4 (stimulus–response position: 1, 2, 3, or 4) × 2 (age: younger or older adults) × 2 (hand placement: adjacent or overlapped) ANOVAs (see Table 3 and Figures 7 and 8).

Reaction Time

Responses were slower overall for older adults (*M* = 712 ms) than for younger adults (*M* = 532 ms), $F(1, 28) = 27.64$, *MSE* = 753,617, $p < .001$, and for the overlapped hand placement (*M* = 668 ms) than for the adjacent hand placement (*M* = 576 ms), $F(1, 28) = 7.29$, $p = .012$. Those two variables did not interact, $F < 1.0$.

The main effect of precue type was significant, $F(3, 84) = 15.89$, *MSE* = 12,716, $p < .001$. Mean RT was longest for the uninformative cue (*M* = 642 ms), shortest for the left–right cues (*M* = 599 ms), and intermediate for the alternate (*M* = 625 ms) and inner–outer (*M* = 622 ms) cues. The main effect of precue interval was also significant, $F(4, 112) = 25.31$, *MSE* = 15,964, $p < .001$, with RT decreasing as precue interval increased. Precue interval entered into a three-way interaction with age and hand placement, $F(4, 112) = 3.09$, $p = .032$. Older adults showed a larger decrease in RT than younger adults as precue interval increased with the adjacent hand placement, but not with the overlapped hand placement.

Precue type and precue interval interacted, $F(12, 336) = 6.10$, *MSE* = 7,080, $p < .001$. That interaction reflected primarily that RT for the uninformative cue was relatively unaffected by precue interval, whereas RT for the informative precue types decreased as interval increased. Precue type also interacted with age, $F(3, 84) = 5.09$, $p = .003$, with the precuing benefits generally being larger for older than younger adults. More specific analyses of that interaction showed that the benefit for the informative precues compared with that for the uninformative cue was of similar magnitude for older (*MD* = 30 ms) and younger (*MD* = 25 ms) adults, $F < 1.0$, whereas the three informative precue types interacted with age, $F(2, 56) = 5.88$, $p = .005$ (older adults' mean RTs were 675, 717, and 722 ms for the left–right, inner–outer, and alternate precue types, respectively; younger adults' mean RTs were 524, 526, and 527 ms, respectively). Older adults showed a larger overall advantage than the younger adults for the left–right cues over the inner–outer and alternate location cues.

The analysis of the three informative precue types also showed a four-way interaction of precue type and age with precue interval and hand placement, $F(8, 224) = 2.31$, $p = .027$. For the adjacent placement, the interaction of the

TABLE 3. Mean Reaction Time and Percentage Error for the Adjacent and Overlapped Hand Placements in Experiment 3 as a Function of Precue Type, Precue Interval, and Age Group

	Precue interval									
	100 ms		500 ms		1,000 ms		1,500 ms		2,000 ms	
Precue type	RT	%	RT	%	RT	%	RT	%	RT	%
Adjacent placement: younger adults										
Uninformative	497	0.0	505	0.78	497	0.0	517	0.0	500	0.0
Left–Right	501	1.56	467	0.63	456	1.88	478	0.78	463	0.0
Alternate	536	2.50	498	1.93	488	0.0	470	1.04	460	0.52
Inner–Outer	518	1.04	489	1.41	469	0.63	465	0.0	446	1.04
Adjacent placement: older adults										
Uninformative	703	0.52	681	1.15	703	0.78	676	0.52	697	0.0
Left–Right	704	2.19	646	0.0	605	0.0	557	0.52	589	0.0
Alternate	723	1.15	718	4.48	720	1.25	608	1.88	624	1.77
Inner–Outer	730	1.77	715	4.32	686	1.30	613	2.34	610	2.03
Overlapped placement: younger adults										
Uninformative	606	1.04	607	0.52	591	1.15	589	0.52	590	1.77
Left–Right	615	1.77	609	3.33	577	1.15	538	2.40	534	1.30
Alternate	615	3.91	613	2.97	562	1.15	513	1.15	519	1.67
Inner–Outer	620	2.29	607	2.40	558	1.30	543	1.67	549	0.78
Overlapped placement: older adults										
Uninformative	780	2.29	782	1.30	778	1.25	791	0.0	761	0.0
Left–Right	749	6.51	735	1.77	744	2.92	713	4.79	703	2.97
Alternate	795	5.10	792	2.71	777	3.33	732	5.05	730	5.78
Inner–Outer	827	4.53	783	4.53	772	2.40	717	2.29	719	2.55

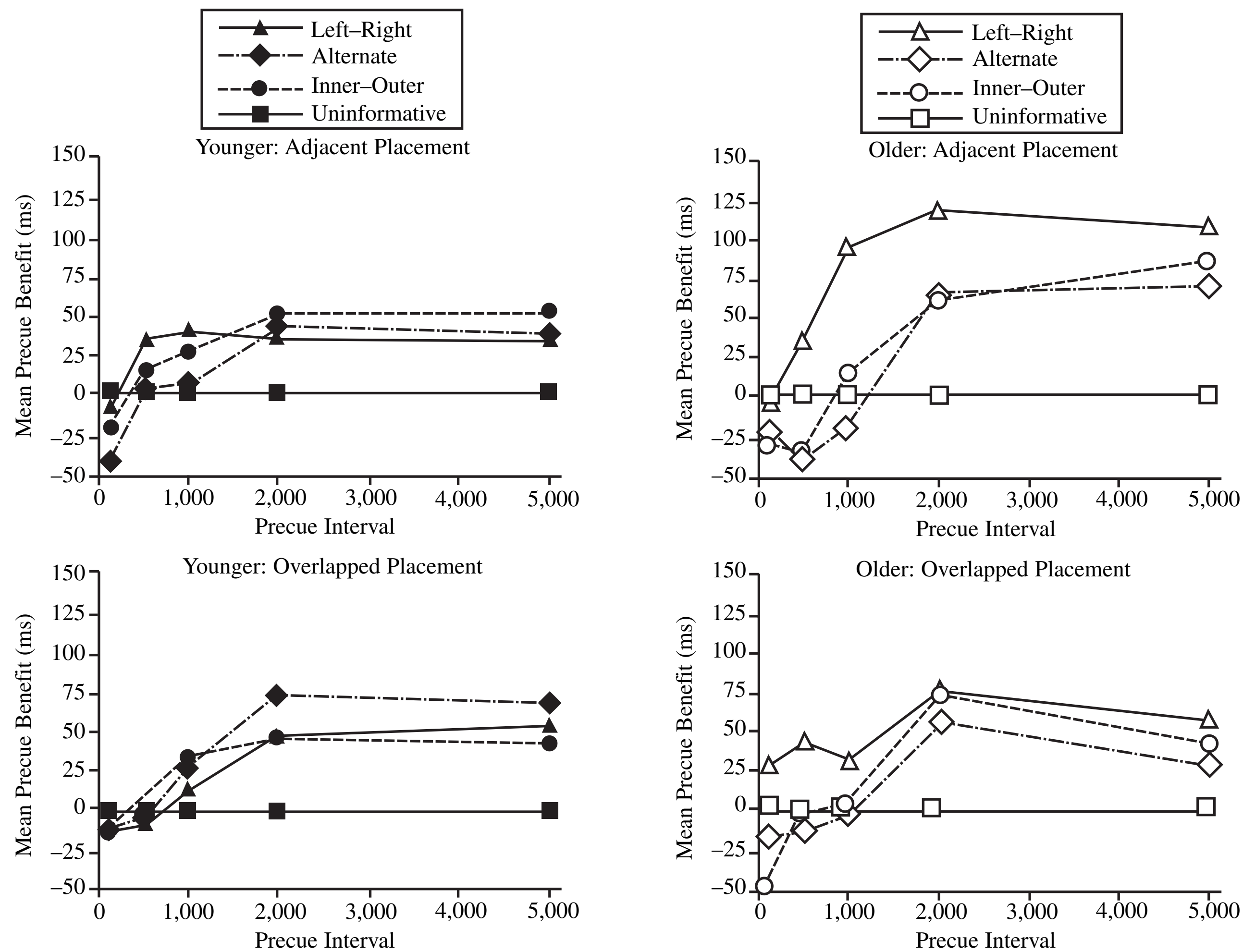

FIGURE 7. Mean precuing benefits (reaction time [RT] for each precue type minus RT for the uninformative precue) for the adjacent and overlapped hand placements in Experiment 3 as a function of age group and precue interval.

remaining three variables was significant, $F(8, 112) = 3.95$, $p = .002$. Both younger and older adults showed an advantage for the left–right cues at the short precuing intervals that decreased at the longer ones (see Figure 7). The advantage was absent for the younger adults by 2,000 ms, Fs < 1.0 for both that interval and the 5,000-ms interval, and was present for the older adults at 2,000 ms, $F(2, 14) = 4.70$, $p = .028$, but not at 5,000 ms, $F < 1.0$. For the overlapped placement, that three-way interaction was not significant, $F < 1.0$, indicating roughly similar time courses for the older and younger adults.

The remaining significant effects in the primary analysis involved stimulus–response position. That variable showed a main effect, $F(3, 84) = 35.76$, $MSE = 37{,}772$, $p < .001$ (see Figure 8). As in Experiment 1, that effect was primarily the result of the longer RT for the two inner positions ($M = 662$ ms) than for the two outer positions ($M = 583$ ms). In addition, the two-way interaction of position with precue interval was significant, $F(12, 336) = 2.48$, $MSE = 7{,}113$, $p < .009$, as was the three-way interaction of those variables with precue type, $F(36, 1008) = 1.66$, $MSE = 5{,}914$, $p < .022$. The two-way interaction reflected the finding that the difference between the inner and outer positions decreased from the 500-ms interval onward (Ms = 82, 97, 87, 75, and 54 ms, respectively). The three-way interaction, which accounted for only a small amount of variance, indicated that the pattern shown by the two-way interaction was most evident for the left–right and alternate precue types.

We performed a separate analysis to assess whether the position effects differed at short and long precuing intervals. For that analysis, we grouped the data into short (100, 500, and 1,000 ms) and long (2,000 and 5,000 ms) intervals and analyzed them with interval as a variable. Interval entered into a two-way interaction with stimulus–response position, $F(3, 84) = 45.79$, $p < .001$, and three-way interactions of those variables with age, $F(3, 84) = 3.78$, $p = .033$, and precue, $F(9, 252) = 2.96$, $p = .005$. Position had a significant effect at both the short and long intervals. At the short intervals, RT was more than 80 ms longer for the inner positions than for the outer ones; at the longer intervals, the

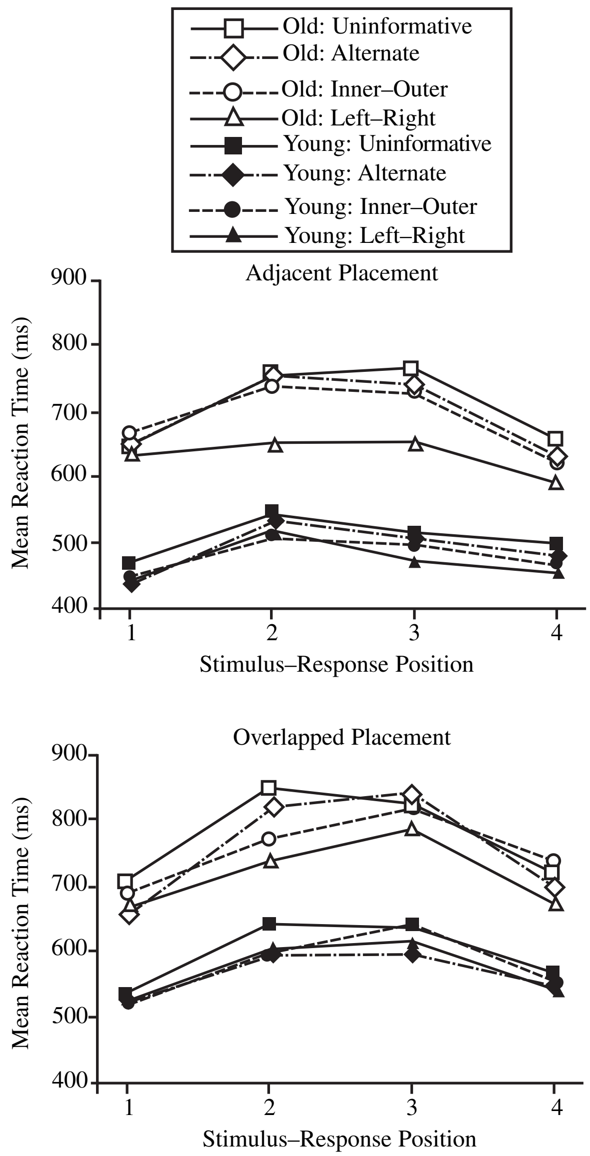

FIGURE 8. Mean reaction time for the adjacent and overlapped hand placements in Experiment 3 as a function of age group, precue type, and stimulus-response position.

difference was only 65 ms. The interaction of position with age was not significant for either short or long intervals alone, although the slowing for the center positions tended to be relatively larger for older than for younger adults at the long intervals than it was at the short ones. The interaction of position with precue type was not significant at the short intervals but was at the long ones. At the long intervals, the function was much flatter for the left–right precue condition than for any of the other conditions.

Percentage Error

The PE data showed a main effect of hand placement, $F(1, 28) = 7.18$, $MSE = 154$, $p = .012$; PE was higher for the overlapped placement (M = 2.42%) than for the adjacent placement (M = 1.11%). The main effect of age was marginally significant, $F(1, 28) = 4.17$, $p = .051$, and age did not interact with hand placement. Older adults (M = 2.27%) tended to make more errors than younger adults (M = 1.26%). The main effects of precue type, $F(3, 84) = 7.73$, $MSE = 48.1$, $p < .001$, and precue interval, $F(4, 112) = 3.04$, $MSE = 39.8$, $p = .020$, were also significant. The fewest errors were made for the uninformative cue (M = 0.71%), followed by the left–right (M = 1.79%), inner–outer (M = 2.03%), and alternate (M = 2.52%) cues. The overall error rate decreased as the precuing interval increased.

The main effect of stimulus–response position was significant, $F(3, 84) = 20.59$, $MSE = 57.8$, $p < .001$. As in Experiment 1, that effect resulted primarily from the larger PE for the two inner positions (M = 2.9%) than for the two outer positions (M = 0.65%). Position interacted with age, $F(3, 84) = 3.61$, $p = .032$, and with the combination of age and precue type, $F(9, 252) = 2.50$, $MSE = 34.8$, $p = .021$. The former interaction indicated that this difference was larger for the older adults (MD = 3.2%) than the younger adults (MD = 1.2%). The latter interaction was a consequence of the older adults showing more errors than the younger adults for the inner positions in the alternate and inner–outer precue types, but not for the other two precue types.

Discussion

With the adjacent hand placement, both younger and older adults showed a larger benefit for the left–right cues at precuing intervals of 1 s or less. With longer time to prepare, all informative precue types ultimately showed benefits that did not differ significantly in size; the difference between the informative precue types became nonsignificant for the older adults only at the longest precuing interval. With the overlapped placement, only the older adults showed a clear advantage for the left–right cues over the other informative precue types at the short precuing intervals. By the 2- and 5-s intervals, however, the older adults showed benefits for all informative precue conditions, which at the 5-s interval did not differ significantly in size. Thus, older adults are able to use precue information effectively even when they are unsure about the time that will be available for selection and preparation of cued responses.

There are several differences in the results of this experiment, in which the precuing interval was randomized across trials, and those of Experiment 1 (and Experiment 2), in which interval was blocked. First, with both hand placements, older adults did not show much tendency for RT to increase as the precuing interval increased in this experiment, whereas they did in the previous experiments. The relatively flat functions for the uninformative cue suggest that when precuing intervals were randomized, older adults maintained a similar general level of preparedness to respond during the entire period after onset of the cue stimulus. The fact that RT was slower for the uninformative cue condition in Experiment 3 than it was in Experiment 1 (collapsed across the precuing intervals that were the same for both experiments, *MD*s = 70 and 32 ms for adjacent and overlapped placements, respectively) at all but the 2-s interval suggests that when precuing intervals were randomized, the older adults were not prepared to respond as fast as possible to target stimuli that appeared shortly after the precue.

A second difference is that the older adults showed unambiguous use of the precue information with the overlapped hand placement in this experiment, but little evidence of such use at any precuing interval in Experiment 1. We suggested in the Discussion of Experiment 1 that, with the overlapped hand placement, the older adults had difficulty using the precue information within the available time for intervals less than 2 s, and the difficulty they experienced in the earlier blocks led them to adopt a strategy of not using the precue even in the 2-s trial block. The question is, if that is the case, then why would the older adults use the precue information when long and short precuing intervals were randomized in the present experiment? The lengthened RT at the short intervals in this experiment compared with that in Experiment 1 indicated that when the intervals were randomized, the older adults could not adopt a strategy of being prepared to respond quickly to a target stimulus presented immediately after the precue. Moreover, the interval was of sufficient duration (2 s or longer) on 40% of the trials to allow participants adequate time for preparation of any cued subset. Consequently, it was beneficial to adopt a strategy of using the precue information when the intervals were randomized.

In addition to showing use of the precue information with the overlapped placement in this experiment, at intervals of less than 2 s the older adults benefited only from the left–right cues. As noted, this left–right precuing advantage is a relatively common outcome, suggestive of easier conversion of those precue stimuli into specific preparation for the cued subset because of the salience of the left–right distinction (e.g., Adam et al., 2003; Reeve & Proctor, 1984). That older adults using the overlapped placement in Experiment 1 showed no benefit for the left–right cues at short (or long) precuing intervals implies that, at least with the overlapped placement, the precuing benefits for the left–right cues are not automatic, in the sense of being independent of the participants' intentions. When participants adopt a strategy of being prepared to respond immediately to the location of the imperative stimulus rather than using the precue information, as apparently was the case in Experiment 1, not only are the benefits for the cues that involve effortful stimulus–response subsets eliminated, but so also are those for the cues that are more natural to process.

GENERAL DISCUSSION

The issue of whether older adults can benefit from advance information as much as younger adults or whether older adults show a deficit in using such information is important from both theoretical and applied perspectives. In theory, the answer to that question can help to pinpoint the exact nature of the processing changes that occur with age. In practice, the answer should indicate whether one can reduce the costs of overall slowing that occur with age by providing older adults with advance information that cues them as to what events are likely to occur and what actions are likely to be required.

Several experiments conducted with movement-precuing tasks have yielded results indicating that older adults benefit at least as much as younger adults from precue information, although they need a longer time to make use of that information (Chua et al., 1995; Stelmach, Goggin, & Amrhein, 1998; Stelmach, Goggin, & Garcia-Colera, 1987; for a review, see Proctor et al., 2005). Those studies have shown no deficit in the ultimate level of preparation that older adults can attain for subsets of responses made by the same hand or different hands. In contrast, Adam et al. (1998) reported results from a key-press precuing task that they described as showing an age-related deficit for preparing finger responses on different hands. In the present study, we examined whether that age-related deficit is a limitation in the ability to prepare two fingers on different hands or to select precued responses for combinations of locations that require more effort to process. We also examined whether the deficit is one of needing more time to select and prepare the cued responses or of the ultimate level of preparation that can be attained. We accomplished those examinations by adding an overlapped hand placement that allowed us to dissociate effects caused by the hand distinction from those caused by spatial locations (Reeve & Proctor, 1984) and by extending the precuing intervals to 5 s. The results reconcile the findings of Adam et al. with those from the other precuing studies in providing evidence that although older adults need longer than younger adults to prepare the more effortful subsets of cued responses, there is little or no age-related deficit in the maximum level of preparation that can be achieved for responses on same or different hands.

In Experiment 1, we replicated the results obtained by Adam et al. (1998) when participants performed the key-press precuing task with a normal hand placement, as in their study. Younger adults showed roughly equivalent benefits for all pairs of cued responses at precuing intervals of 1.5 and 2.0 s, but older adults showed larger benefits for precuing the two leftmost or two rightmost locations than for the other informative precue types. As in the study of Adam et al., however, at those intervals older adults did show some benefit relative to the uninformative cue for the precue types involving responses on different hands. Although the overlapped hand placement showed the common finding for young adults, that the pattern of precuing benefits is determined primarily by the spatial locations that are cued and not whether they are on the same or different hands, the older adults showed little or no precuing benefits for the overlapped hand placement.

We obtained evidence in Experiment 2 that the precuing deficit for older adults in Experiment 1 was caused primarily by insufficiently long time intervals that did not allow them to use the precue information. When the intervals ranged between 2,000 and 5,000 ms in Experiment 2, substantial precuing benefits were evident for all informative precue conditions at all intervals, for both younger and older adults. Moreover, older adults showed larger precuing benefits than did younger adults, particularly with the overlapped hand placement, for which they had shown little benefit for any informative precue type in Experiment 1. Thus, older adults generally need more time than younger adults to select and prepare responses based on the precue, but they are able to achieve benefits much like those shown by younger adults if allowed sufficient time.

Adam et al. (1998) concluded that it was not plausible that older adults would show the same benefits as younger adults at precuing intervals longer than 2 s because the older adults' RT was an increasing function of the interval duration. That pattern was evident in Experiments 1 and 2 of the present study, with RT for older adults increasing as the cue–target interval increased in all cases for which the cue was uninformative and in many cases for the informative precues as well. The increase in RT apparently reflected difficulty in maintaining a readiness, or set, to respond. Contrary to Adam et al.'s intuitions, however, that did not preclude the older adults from showing a large benefit for all informative precue types at the long intervals used in Experiment 2. Thus, the ability to prepare selectively for the cued stimulus–response subset does not seem to depend on the ability to maintain a general level of readiness to respond quickly. That finding is similar to that of Bonin-Guiallaume, Possamaï, Blin, and Hasbroucq (2000), who found that older adults maintained the same benefit for a compatible mapping over an incompatible mapping with a 2,500-ms foreperiod, even though their responses were 60 ms slower than with a 500-ms foreperiod.

Although Adam et al. (1998) used a procedure in which the precue interval was held constant within a block of trials, a more common procedure is to vary the interval randomly within a trial block (see, e.g., Miller, 1982; Reeve & Proctor, 1984). With randomized presentation, participants do not know how much time is available for preparation before onset of the imperative stimulus, which makes the task more difficult and, therefore, could possibly introduce age-related differences in precue use. Thus, in Experiment 3, we randomized, rather than blocked, the precue interval. In that case, both younger and older adults showed benefits for all informative precue types at the two longest precuing intervals of 2,000 and 5,000 ms. Thus, even when older adults do not know when the target stimulus will appear, they can benefit from a precue that specifies two responses on the same hand or on different hands, as long as they have sufficient time to prepare. This experiment, along with Experiment 2, therefore, showed little evidence that older adults are deficient at being able to prepare two fingers on different hands as opposed to two fingers on the same hand. With the randomized presentation of intervals used in Experiment 3, RT with the uninformative cue did not increase systematically as interval increased, suggesting that the older adults maintained a similar state of preparedness to respond across the different trial intervals.

For displays of the type used in the current experiments, evidence indicates that the left–right grouping of the four stimulus and response locations is salient (Reeve & Proctor, 1984, 1990). Within the context of Adam et al.'s (2003) grouping model, which emphasizes the salience of the left and right subgroups, the performance of older adults can be characterized as follows. The stimulus and response sets are organized into two subgroups on the basis of the left–right spatial distinction for the older adults, as they are for the younger adults. With the adjacent hand placement, the automatic selection of cued responses that occurs for the left–right precues, which correspond with the salient subgroups, does not suffer much with age. However, the nonautomatic, effortful processes required for selection of cued responses for other pairs of locations operate less efficiently for older than for younger adults, thus requiring more time.

The additional difficulty introduced by the overlapped hand placement apparently caused older adults not to engage in much selective preparation in Experiment 1, even for the nominally automatic left–right precues, when the longest precuing interval was 2 s. That the absence of preparation was a strategy adopted by the older adults is suggested by the fact that all informative precue types showed substantial benefits at this same precuing interval of 2 s when it was tested with blocks of 3-, 4-, and 5-s intervals in Experiment 2 or randomly intermixed with intervals of up to 5 s in Experiment 3. The provisional conclusion, supported by the analysis presented in the Discussion section of Experiment 2, is that the older adults chose not to use the precue information for the difficult overlapped hand placement when they had experienced trial blocks that did not allow sufficient time for the precue information to be used appropriately.

Our experiments replicated the finding by Adam et al. (1998) of an inverted U-shaped stimulus–response position effect, for which RT was longer for the two inner positions than for the two outer positions, with the position effect being larger for older adults than younger adults. Adam et al. attributed that position effect to the greater confusion caused by the inner than the outer positions that arises from the fact that the inner positions have two adjacent neighbors, whereas the outer ones have only one. In their study, the position effect was smaller for the left–right cues condition than for the other informative precue types and the uninformative cue. Adam et al. suggested that the reduced position effect for the left–right cues resulted from their correspondence with the salient left–right grouping feature of the stimulus and response sets, which allowed the task to be effectively reduced to a choice between two locations when either the two leftmost or two rightmost positions were precued. Our Experiment 1, in which we used the same precuing intervals as Adam et al. did, showed a similar tendency for the adjacent hand placement but not for the overlapped hand placement. Experiment 3, in which precuing intervals were randomized within trial blocks, also showed the pattern of smaller position effects for the left–right cues with the adjacent hand placement, but, in that case, only for older adults. In contrast, with the long precuing intervals used in Experiment 2, the position effects for all of the informative precue types were greatly reduced relative to those for the uninformative condition with both hand placements and especially for the older adults. That outcome implies that given sufficient time to prepare, the inner–outer and alternate pairs of locations can also be treated as a two-choice task instead of a choice between two of four locations.

A major issue in studies of cognitive aging has been the extent to which declines in task performance for older adults are a function of a general decrease in information-processing speed or of more specific losses, which Span et al. (2004) called the global-speed and specific-gain/loss hypotheses. Span et al. evaluated those hypotheses by having college-aged and older adults perform a set of RT tasks intended to engage or minimize executive control functions (e.g., response selection, response suppression, and working memory). They controlled for global speed differences by using performance on the nonexecutive tasks as a covariate in analyzing performance on the executive control tasks. Span et al. found that controlling for global speed in that manner did not eliminate the difference in performance on the executive control tasks for older and younger adults. Their results suggested that executive control functions associated with the frontal lobes are more affected by advanced age than are other functions. The present findings are in general agreement with that conclusion. Although the deficit in using precue information exhibited by older adults is not structural or a limit on the ultimate level of preparation that can be attained, it also apparently is not a consequence of general slowing. Those precue conditions that require little effort on the part of individuals to select and prepare the precued subset are unimpaired in older adults in comparison with those that require effort. Thus, the age-related precuing deficit seems to be primarily one of attentional resources and cognitive control.

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NOTE

1. In the Discussion section of their Experiment 2, Adam et al. (1998) noted Reeve and Proctor's (1984) findings, indicating, "The hand-cued advantage is really an advantage for the two left-most and two right-most stimulus–response locations, not for the left or right hand per se (Reeve & Proctor, 1984, Experiment 3)" (p. 879). They also briefly described an account similar to that developed more fully by Adam et al. (2003), stating, "The substantial aging effect for the finger-cued and neither-cued conditions and the relative absence of such an effect for the hand-cued condition might be attributed to the notion that advancing age is accompanied by a reduction in attentional resources . . . , although automatic processes are left intact" (p. 879). However, because Adam et al. (1998) repeatedly referred to the deficit as one of preparing responses on different hands throughout most of their article, including the abstract and conclusion, we think it is fair to describe their characterization of the results as emphasizing an anatomical basis.

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