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Ideomotor-Compatible Tasks Partially Escape Dual-Task Interference in Both Young and Elderly Adults

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Under most circumstances, it is not possible to carry out central processing for 2 tasks at the same time; effectively there is a bottleneck. Nevertheless, in 2 experiments it is demonstrated here that both younger and older adults are able to partially bypass the bottleneck in a psychological refractory period procedure, even without extensive training, when the 2nd of the 2 tasks is a saccade or a body tilt in the direction of rotation of a visual stimulus. Consistent with earlier research, the findings showed that younger adults can bypass when the second task has ideomotor-compatible stimuli and responses. Most strikingly, they demonstrated that bypass can also occur in older adults. Overall, the findings are inconsistent with any categorical claim that younger adults can bypass the dual-task bottleneck whereas older adults cannot. The construct of ideomotor-compatible tasks may comprise 2 quite different classes of experimental procedures.

Keywords: aging, psychological refractory period, dual-task interference, ideomotor compatibility

In managing two tasks when one task arrives at the same time as or shortly after another, the two cannot be executed simultaneously under most circumstances. The processing of one must wait until the processing of the other is completed. Under certain conditions, however, younger adults appear able to carry out processing of a second task even as the first task is being processed. The question addressed here is whether older adults show a similar ability or whether the ability has been lost with advancing age.

The management of dual tasks has been extensively studied using a procedure in which the stimulus for one task is presented and then, after a variable stimulus onset asynchrony (SOA), the stimulus for a second task is presented. The SOAs can vary from 0—simultaneous onset—through very short (e.g., 15 ms) to longer intervals of 1,000 ms or more, at which point the tasks are sufficiently separated that the first is complete before the second arrives. The typical findings are that reaction time (RT) to Task 1 is relatively unaffected by the SOA whereas RT to Task 2 increases monotonically as SOA becomes shorter. This period of slowing on Task 2 is called the *psychological refractory period* (PRP) effect. The most common explanation for the PRP effect is that there is a bottleneck such that only one task can be processed at a time (cf. Craik, 1947; Welford, 1952). The bottleneck explanation postulates three stages: an early stage comprising processes such as perceptual identification of the stimulus, a middle stage comprising central processes such as response selection, and a late stage comprising processes such as response execution. The explanation holds that the bottleneck is in response selection, which can only be carried out for one task at a time. The assumption is that the perceptual identification stages and response execution stages of one task can be carried out in parallel with any stage of the other task. This is called the *response-selection bottleneck* (RSB) model of the PRP effect. There is debate about the nature of the bottleneck. Some hold that it is an immutable part of the structural architecture (Pashler, 1994, 1998). Others argue that the architecture is flexible and the bottleneck is strategically optional (e.g., Meyer & Kieras, 1997a, 1997b) or adjustable in its restrictions (e.g., Tombu & Jolicœur, 2005). Yet another view is that some aspects of response selection can escape or *bypass* the bottleneck while other aspects are blockaded (e.g., Hommel, 1998). If these latter views are to be maintained, there must be empirical evidence consistent with bottleneck bypass. There is. We will describe two bodies of evidence: bypass after extensive training and bypass without extensive training.

Evidence for a bypass of the response-selection bottleneck has been found with subjects given thousands of training trials, simultaneous onset of the two stimuli (a 0-ms SOA), and instructions to respond to both tasks at the same time (Schumacher et al., 2001). Hazeltine, Teague, and Ivry (2002) replicated this result. They did note that it remains possible that one or both tasks were so well learned that central processing of the two did not conflict, that is that there was a bottleneck but it remained latent (i.e., an absence of temporal overlap between the two response-selection stages whose durations became short due to training). Anderson, Taatgen, and Byrne (2005) were able to simulate the near-perfect time sharing obtained by Hazeltine et al. with a model incorporating a

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central bottleneck. It is not necessary that all trials be 0-ms SOA. Using a variable SOA, Ruthruff, Van Selst, Johnston, and Remington (2006) found evidence that 4 out of 18 individuals had eliminated the bottleneck after extensive practice. Maquestiaux, Laguë-Beauvais, Ruthruff, and Bherer (2008) used a procedure similar to that of Ruthruff et al. They increased the amount of training by about 15%, although they provided training only on Task 2, which was simplified from that used in the earlier study so as to be less attention demanding. Maquestiaux et al. found evidence that 17 out of 20 individuals showed the signatures of bottleneck bypass. Maquestiaux, Laguë-Beauvais, Ruthruff, Hartley, and Bherer (2010) applied exactly the same procedures as Maquestiaux et al. (2008) to 12 older adults and found that only 1 showed signs of possible bottleneck bypass. Maquestiaux, Didierjean, Ruthruff, Chauvel, and Hartley (2013) used a procedure similar to that of Maquestiaux et al. (2010) except that they doubled the amount of training on the task that would become Task 2 to 10,080 trials. Mean Task 2 RT after training was nearly identical to that of the younger adults tested by Maquestiaux et al. (2008). Close examination of the rates of dual-task response reversals—when the response to Task 2 is given before the response to Task 1—indicated that 2 of the 10 older participants may have been able to bypass the bottleneck on about half of the trials. Maquestiaux et al. (2013) concluded, with only 3 of 22 older adults across two studies showing any sign of bottleneck bypass, that the ability to automatize novel tasks is largely lost in old age. By contrast, Strobach, Frensch, Müller, and Schubert (2012b) reported that dual-task costs were reduced to very low levels in 8 older adults, using a procedure very similar to that of Schumacher et al. (2001). The tasks were simple and were presented simultaneously, rapid and simultaneous responding was emphasized, and extensive training was given. The same authors had previously found that younger adults achieved very small dual-task costs after 8 sessions of training, whereas older adults could not achieve that level even after 12 sessions (Strobach, Frensch, Müller, & Schubert, 2012a). When Strobach et al. (2012b) extended the training to 21 sessions, with the tasks simplified after 16 sessions, the older adults were able to match the performance of the young. As we noted earlier, very small dual-task costs do not guarantee that the response-selection bottleneck has been bypassed. A viable alternative interpretation is that the response-selection bottleneck is latent (i.e., the two response-selection stages are never demanded at the same time). Nevertheless, we can say cautiously that, although it may be possible under certain circumstances, older adults have largely not demonstrated bottleneck bypass in situations in which the tasks may not be simultaneous.

One class of situations in which some have argued that bottleneck bypass is possible without training is that of tasks involving word reading, such as phoneme judgment, word recognition, and lexical decision tasks. For most adults, reading is an easy and an extremely well-practiced task, so much so that it might be thought of as nearly reflexive or automatic. The hundreds of demonstrations of the Stroop (1935) phenomenon, in which the presence of a task-irrelevant color word facilitates or interferes with the naming of a displayed color, confirm this (MacLeod, 1991). If the second of two tasks involves or can be facilitated by reading, can central processing on that task begin before central processing on the first task is complete or must it wait until the central bottleneck has cleared? To address this question, McCann, Remington, and Van Selst (2000) gave a pitch discrimination as the first task and a lexical decision or word naming task as the second task with SOAs between the tasks of 100 to 800 ms. High-frequency words were responded to more quickly than low-frequency words, but this slowing combined additively with the slowing due to decreasing SOA. They interpreted this result to mean that the effect of word frequency, and therefore the effects of visual word processing generally, must come after the RSB (see also Pashler, 1994, Principle 4).

Subsequent experiments have obtained different results (Allen et al., 2002; Cleland, Gaskell, Quinlan, & Tamminen, 2006; Gaskell, Quinlan, Tamminen, & Cleland, 2008; Lien, Ruthruff, & Johnston, 2006; Rabovsky, Álvarez, Hohlfeld, & Sommer, 2008), reporting instead that the effects due to word reading are smaller at very short SOAs than they are at long SOAs, at which there should be little interference between the tasks. For example, in a lexical-decision task, high- and low-frequency words are identified as words faster than nonsense strings are identified as nonwords, but the difference between high- and low-frequency words is smaller at short SOAs than at long SOAs (Allen et al., 2002; Cleland et al., 2006; Lien et al., 2006; Rabovsky et al., 2008). That is, there was a subadditive interaction with RTs for high- and low-frequency words converging with decreasing SOA. McCann et al. (2000) had found some evidence for subaddivity but discounted it. The RSB model predicts such subadditive effects when Task 2 precentral, perceptual processes are carried out in parallel with Task 1 precentral or central processing during the cognitive slack when Task 2 central processing is postponed until the bottleneck opens (see Pashler, 1994, Principle 3). The presence of a subadditive interaction does mean that some aspect of the reading of the word (Task 2) must have taken place at the same time as the precentral or central stages of processing of Task 1. But that aspect must be part of the early, perceptual identification stages of the lexical-decision task, so it is not evidence for central processing of Task 2 occurring before the bottleneck.

Evidence for at least partial bypass of the response-selection bottleneck has also been found in a different group of studies that also do not involve extensive practice. Pashler, Carrier, and Hoffman (1993, Experiment 1) used a PRP procedure in which Task 2 was to make a saccade to a peripheral target. RT to Task 2 decreased from 245 ms at 50-ms SOA to 194 ms at 750-ms SOA, a PRP effect ($RT_{SHORTEST\ SOA} - RT_{LONGEST\ SOA}$) of only 51 ms. By contrast, when the task was to make a saccade in the direction indicated by a central color cue (Experiment 3), the PRP effect was approximately 160 ms (estimated from Figure 3 in Pashler et al., p. 63). Further evidence that responses were not being postponed by a central bottleneck in their Experiment 1 is that at the 50-ms SOA, the mean saccade for Task 2 was completed 205 ms faster than the mean manual response to Task 1. Pashler et al. speculated that eye movements to a peripheral target may be controlled by deeper, more primitive systems involving the superior colliculus whereas centrally cued eye movements are controlled by the frontal lobes. The apparently reduced or absent bottleneck in their Experiment 1 may be an example of what Greenwald (1972) and Greenwald and Shulman (1973) have termed *ideomotor compatibility*.

Ideomotor compatibility is a special case of compatibility between stimulus and response. Ideomotor theory postulates that “responses are centrally coded by representations of their sensory feedback” (Greenwald, 1972, p. 52). Thus a connotative definition of ideomotor compatibility is that a stimulus closely resembles the sensory feedback after the response to the stimulus is made. In such a case, no central decision may be needed, and it may be possible to bypass any limited capacity bottleneck. As a denotative definition, Greenwald (1972) describes procedures in which a word is said aloud in response to hearing it said and in which a joystick is moved in the direction indicated by an arrow. But, for example, saying the word *left* in response to a left-pointing arrow and *right* to a right-pointing arrow would be stimulus-response compatible, but not ideomotor compatible. Using ideomotor compatible tasks, Greenwald (1972) found little difference between tasks done alone and in a dual-task situation and concluded that the bottleneck had been bypassed. Greenwald (1972) used only a 0-ms SOA. Lien, Proctor, and Allen (2002) used SOAs varying from −50 ms (the stimulus for Task 2 preceded that for Task 1) to 1,000 ms and failed to replicate Greenwald's finding, observing a significant PRP effect.

There was considerable debate about the reasons for the failure to replicate (Greenwald, 2003, 2004, 2005; Lien, Proctor, & Ruthruff, 2003; Lien, McCann, Ruthruff, & Proctor, 2005b); nevertheless, it was the case that Lien et al. (2002) did find smaller PRP effects with ideomotor compatible stimuli and responses than with those that were merely stimulus-response compatible. Subsequently, Lien, McCann, Ruthruff, and Proctor (2005a) showed that a sufficient condition for reduced PRP effects was the presence of an ideomotor compatible Task 2. To explain these results, they proposed an *engage-bottleneck-later model* in which some aspects of the central processing of Task 2 could begin before the central stage of Task 1 was completed and the bottleneck opened. Those aspects might be thought of as automatically activated (cf. Hommel, 1998). This model is represented in Figure 1. In this model, PRP effects are still observed at short SOAs with ideomotor-compatible tasks, but they are reduced relative to non-ideomotor-compatible tasks. This model clearly contrasts with one in which the ideomotor-compatibility simply made the response execution for Task 2 faster. In the RSB model, "manipulating the duration of stages at or after the bottleneck in Task 2 to a given extent will . . . slow RT2 to exactly the same extent, regardless of the SOA" (Pashler, 1994, Principle 4, p. 224). That is, the effect of introducing ideomotor compatibility would be additive with the effect of SOA if it simply made response execution faster.

The Present Research

Situations that may allow partial bypass of the response-selection bottleneck through ideomotor compatibility of stimulus and response have not been explored in older adults (but cf. Grabbe & Allen, 2012, who examined cross-task compatibility in a hybrid design). That was the purpose of the two experiments reported here. Experiment 1 was a conceptual replication of the study of Pashler et al. (1993) with Task 2 requiring a saccade in the direction of rotation of a stimulus photograph. In Experiment 2, Task 2 required a body tilt in the direction of the stimulus rotation. In a comparison condition in both experiments, the response was to press one of two keys, the left key for a rotation to the left and the right key for a rotation to the right. The experimental conditions were presumably ideomotor compatible whereas the comparison condition was merely stimulus-response compatible. To avoid possible output interference between the two tasks, Task 1 in each condition was to say aloud the color of the frame surrounding the photograph, a different response modality from Task 2. The stimuli were both visual but did not overlap, so input interference should have been minimal. What results could we expect? With younger adults, we would expect that the PRP effect would be reduced in the ideomotor-compatible condition relative to the keypress condition as predicted by the engage-bottleneck-later model. With older adults if, as in the training studies of Maquestiaux et al. (2010) and Maquestiaux et al. (2013), they are not able to automatize part of the processing of Task 2, we should not see this reduction. If, however, these ideomotor compatible connections are automated and at least partially bypass the bottleneck in older adults (as may have occurred in Strobach et al., 2012b), we should see a reduction as in the young. Even if this is observed, we might still expect to see a greater PRP effect in the older adults than in the younger adults even in the ideomotor-compatible conditions. Central processing in older adults is generally slower than in younger adults (Birren, 1974). In the RSB model, anything

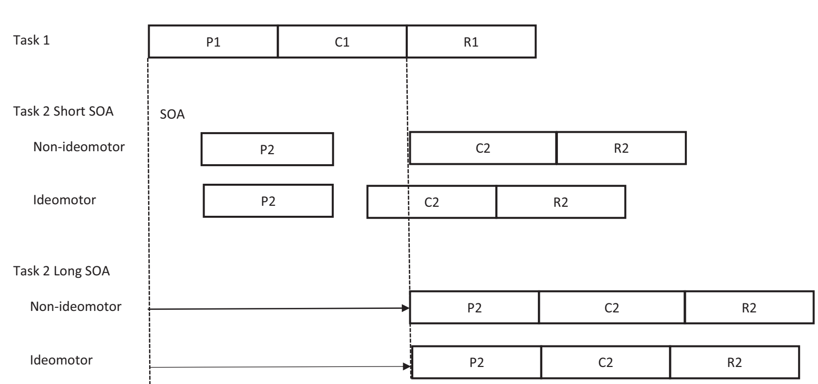

Figure 1. With ideomotor-compatible stimuli and responses, central processing of Task 2 partially escapes the response-selection bottleneck. This was called the *engage-bottleneck-later model* by Lien, McCann, Ruthruff, and Proctor (2005a). SOA = stimulus onset asynchrony; Pn = perceptual stage of Task n; Cn = central stage of Task n; Rn = response execution stage of Task n. Time on a trial runs from left to right.

that slows central processing of Task 1 will exaggerate the PRP effect in Task 2 (Pashler, 1994, Principle 1).

Experiment 1

Participants

Thirty-one younger adults (20 female) and 28 older adults (21 female) participated in Experiment 1. The younger adults were primarily undergraduate students; the older adults were volunteers from the local community. The younger adults averaged 21.00 years of age ($SD = 1.54$ years), reported an average of 14.12 years of education ($SD = 1.24$ years), and rated their health, on average, 8.86 using a scale on which 10 was Excellent ($SD = 0.82$). The older adults averaged 75.07 years of age ($SD = 7.37$ years), reported an average of 16.17 years of education ($SD = 2.58$ years), and gave an average self-rating of health of 8.31 ($SD = 1.20$). Median measured near visual acuity was 20/20 in the younger adults and 20/30 in the older adults. Participants received a stipend of $15 USD for participation. All participants had normal color vision, by self-report.

Tasks

The experimental procedures were controlled by programs written in E Prime (Version 1.0, Schneider, Eschman, & Zuccolotto, 2002) running on Intel Pentium computers. Keypress responses were made with button presses on a response box (Serial Response Box Model 200a, Psychology Software Tools). Vocal responses were sensed by a voice-operated relay in the response box via a microphone attached to a microphone stand and positioned close to the participant's mouth. Saccade responses were sensed by a physiological recording device (Biopac M36R) using AcKnowledge software (Version 4.2), which continuously recorded movement of the eyes and which communicated with the experiment-control computer. Electrodes were placed to the left and right temple with a reference electrode on the forehead. Waveforms were analyzed offline to obtain the RTs (RTs). On each trial, the RT was the difference in time from the onset of the stimulus to the time of the peak rate of change in the position of the eye following the stimulus. Attempts to measure the onset of the saccade more precisely proved unreliable. The point of maximum velocity is later than the true onset of a ballistic saccade but should be in a constant relation to it.

Color task. Each trial began with the presentation of a color photograph of an interior or exterior scene of a building, with strong rectilinear aspects, on a black background. At a viewing distance of approximately 60 cm, on a 27-in. (68.58 cm, diagonal) screen, the photographs subtended 26.57 degrees by 33.82 degrees. Twelve different photographs were used with the photograph chosen at random on each trial. After 1,000 ms, a gray frame 1.79 degrees in thickness appeared around the picture. After another 1,000 ms, the frame color changed either to green or red, with the color randomly chosen on each trial. The participant's task was to say aloud the color of the frame as quickly as possible but without making mistakes. Precisely 3,000 ms were allowed for a response. At the end of the trial, the experimenter entered the verbal response. Feedback about correctness appeared for 750 ms. The intertrial interval was 1,000 ms.

Rotation task. As in the color task, a picture appeared for 1,000 ms, then a gray frame appeared for an additional 1,000 ms. At that point, the framed picture was rotated 20 degrees to the left or right. In the saccade-response conditions, the participant's task was to shift their eyes in the direction of the rotation; in the keypress-response conditions, the participant's task was to identify the direction of rotation by pressing one of two keys on the response box, the left key for a rotation to the left and the right key for a rotation to the right. Exactly 3,000 ms were allowed for a response. For the saccade task, the experimenter used the keyboard to enter the direction of the saccade, determined from the deflections in the online waveform. Feedback about correctness appeared for 750 ms. The intertrial interval was 1,000 ms.

Dual task. Each trial began with a picture displayed for 1,000 ms then a surrounding gray frame appeared for 1,000 ms, at which point the color of the frame changed to green or red. After a variable SOA of 50, 100, 150, 200, 500, or 1,000 ms, the picture and frame were rotated 20 degrees to the left or to the right. The SOA was chosen randomly but with the constraint that all SOAs were used equally often. In both conditions, the participant responded to the frame color by saying the color name aloud. In the saccade-response conditions, the participant responded to the rotation by moving their eyes in the direction of rotation; in the keypress-response conditions, the participant responded by pressing the left or right key on the response box. Precisely 3,000 ms were allowed for each of the responses. Participants were instructed to respond to the frame color and to the rotation, both as quickly as possible but without making errors. To avoid response grouping, they were specifically cautioned not to wait until both stimuli had been seen to make their responses. For saccade responses, the experimenter entered the direction of the saccade. No feedback was given. The intertrial interval was 1,000 ms.

Procedure

All participants first completed one block of 24 practice trials with the color task alone. Then, each participant completed two blocks of trials, one block with a saccade response to the rotation task and another with a keypress response. The order of these two blocks was counterbalanced across participants. In the first block, they completed 24 practice trials with the rotation task alone using the response modality for that block. This was followed by 10 subblocks of 12 dual-task trials with ad lib rest at the end of each subblock. In the second block, they again completed 24 rotation-task practice trials and 120 experimental trials but using the other response modality. Information about gender, age, education, and self-rated health using the 10-point scale on which 10 was excellent was collected, and visual acuity was measured using a Snellen chart viewed at 20 feet (6.10 m) after the experimental tasks were completed.

Results

Analyses of variance were carried out on the mean dual-task RTs for trials on which both responses were correct (resulting in the loss of 2.9% of the trials) and on the proportion correct. Age group (younger or older) was a between-subjects factor. Response modality (saccade or keypress) and SOA (50, 100, 150, 200, 500, and 1,000 ms) were within-subjects factors. Tests for sphericity were carried out and, where significant, the Geisser-Greenhouse corrected probabilities are reported. For 1 younger adult and 8 older adults, saccade onsets could not be reliably determined. With these individuals were dropped, the reported analyses were based on the data of the remaining 30 younger adults and 20 older adults.

Color dual task (Task 1) RT. There was a significant effect of age group, $F(1, 48) = 20.50$, $p < .001$, $\eta_p^2 = .30$, with responses slower in older adults (M = 692 ms, SE = 24 ms) than in younger adults (M = 551 ms, SE = 20 ms). No other effects approached significance.

Color dual task (Task 1) proportion correct. The sole significant effect was a main effect of SOA, $F(5, 240) = 22.05$, $p = .010$, $\eta_p^2 = .05$; however, paired comparisons using the Bonferroni procedure showed no significant differences. The proportion correct was identical for younger and older adults (M = 0.99, SE = 0.01).

Rotation dual task (Task 2) RT. There was a significant effect of age group, $F(1, 48) = 12.82$, $p = .001$, $\eta_p^2 = .21$, with responses slower in older adults (M = 564 ms, SE = 20 ms) than in younger adults (M = 473 ms, SE = 16 ms). There was a strongly significant main effect of response modality, $F(1, 48) = 78.922$, $p < .001$, $\eta_p^2 = .62$, with saccade responses (M = 455 ms, SE = 10 ms) faster than keypress responses (M = 583 ms, SE = 18 ms). The main effect of SOA was also strongly significant, $F(5, 240) = 74.44$, $p < .001$, $\eta_p^2 = .61$, with RTs decreasing monotonically from 50-ms SOA (M = 600 ms, SE = 17 ms) to 1,000-ms SOA (M = 442 ms, SE = 9 ms). The interaction of response modality and SOA was also significant, $F(5, 240) = 45.32$, $p < .001$, $\eta_p^2 = .49$. No interactions involving age group were significant; specifically the interaction of response modality and SOA with age group did not approach significance, $F(5, 240) = 1.23$, $p = .291$, $\eta_p^2 = .02$. Nevertheless, the interaction of response modality and SOA for each age group separately is shown in Figure 2. As can be seen, the significant interaction of response modality and SOA occurred because the effect of SOA was much weaker with saccade responses, $F(5, 240) = 15.17$, $p < .001$, than with keypress responses, $F(5, 240) = 113.09$, $p < .001$. The absence of the three-way interaction means that this result holds true equally for younger and older adults: Examination of the simple interaction effects of SOA and age group showed they were nonsignificant both for saccade responses, $F(5, 240) < 1$, and for keypress responses, $F(5, 240) = 1.11$, $p = .326$. PRP effects, $RT_{50} - RT_{1,000}$, were 245 ms (SE = 18 ms) with keypress responses but only 73 ms (SE = 18 ms) with saccade responses. The PRP effect for saccade responses was not significantly different from the value of 51 ms reported by Pashler et al. (1993), $t(49) = 1.65$, $p = .106$, but was significantly greater than zero.

Rotation dual task (Task 2) proportion correct. The sole significant effect was a main effect of SOA, $F(5, 240) = 3.53$, $p = .004$, $\eta_p^2 = .06$. Bonferroni tests showed that accuracy was higher at SOAs of 100 and 150 ms (M = 0.99, SE = 0.01) than at an SOA of 500 ms (M = 0.98, SE = 0.01) with the others intermediate.

Discussion

The results for younger adults replicate the findings of Pashler et al. (1993). They are completely consistent with the engage-bottleneck-later model of Lien et al. (2005b) in which some part of central processing of Task 2 can be carried out while the central processing of Task 1 is underway. The results for older adults follow exactly the same pattern with the exception that older adults were 91 ms slower than younger adults on average. The results were not consistent with complete bypass of the response selection bottleneck because the PRP effects were nonzero, but it appears that an ideomotor-compatible Task 2 does elicit some automatic processing and it does so for both younger and older adults. This is in contrast with the findings from those studies using extensive training with novel tasks in which younger adults showed benefits not seen in older adults (Maquestiaux et al., 2008, 2010, 2013). It is somewhat consistent with the findings of Strobach et al. (2012b) who found that, after 21 sessions of training with 2 two-choice RT tasks, older adults showed benefits comparable with those achieved by younger adults after 8 sessions with more difficult three-choice versions of the tasks. Combining the present results with previous findings, a reasonable conclusion is that responses that are automatic remain automatic, but that it is very difficult for older adults to automatize new responses except with very large amounts of practice and much simpler tasks than those used in younger adults.

We note that there is some lack of clarity about the concept of ideomotor compatibility. The connotative definition of ideomotor compatibility was that the sensory feedback after the response was identical to the stimulus. This describes the situation when a word is said aloud in response to hearing that word. It is less clear that this applies when a saccade is made in response to a rotation in the visual scene. The effect of the saccade is not identical to the

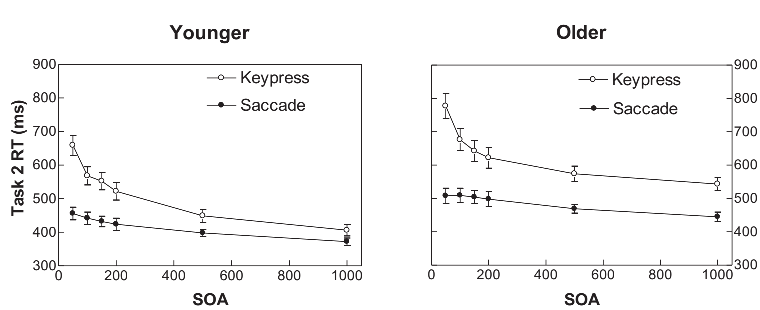

Figure 2. Reaction times (RTs) to rotation task (Task 2) showing interaction of stimulus onset asynchrony (SOA) with response modality (saccade responses or keypress responses) for younger adults (left) and older adults (right) in Experiment 1.

stimulus but is rather to shift the stimulus on the retina. We will return to this issue in the general discussion.

Experiment 2

Arguably, a saccade to a sudden change in the visual periphery is more than ideomotor compatible; it is, in fact, reflexive. For this reason, we carried out a second experiment in which Task 2 was presumably ideomotor compatible but was not reflexive. Instead of making a saccade in response to a rotation in the stimulus photograph, the participant was instructed to shift their weight and tilt their body in the direction of the photograph rotation. A body tilt should be ideomotor compatible in the same way a saccade was. But it would not be reflexive. If, for example, an observer experiences the visual world tilting to the left (as when a boat tips to the left), the reflexive response is to tilt the body in the opposite direction, that is to the right, to maintain the vertical relative to gravity. What results might we then expect with participants tilting their body in the direction of the rotation? For younger adults, we would predict at least partial bypass of the response-selection bottleneck as seen in Experiment 1. For older adults, there are reasons to expect bottleneck-related interference, unlike what was seen in Experiment 1. Posture and gait are more affected by concurrent cognitive tasks in the elderly than in the young (e.g., Liston, Bergmann, Keating, Green, & Pavlou, 2014; Pothier, Benguigui, Kulpa, & Chavoix, 2014; for a review see Woollacott & Shumway-Cook, 2002). This would be expected if postural control required more cognitive effort in older adults than in younger adults. If postural control becomes an effortful, cognitive task in the elderly but remains an automatic, motor task in the young, we might well expect to find evidence that the response-selection bottleneck is bypassed in the young but not in the elderly.

Participants

Seventeen younger adults (11 female) and 16 older adults (11 female), drawn from the same populations as Experiment 1 but who had not participated in Experiment 1, participated in Experiment 2. The younger adults averaged 20.20 years of age (SD = 1.57 years), reported an average of 14.53 years of education (SD = 1.30 years), and rated their health, on average, 8.87 using the 10-point scale (SD = 1.06). The older adults averaged 75.67 years of age (SD = 7.74 years), reported an average of 15.13 years of education (SD = 2.72 years), and gave an average self-rating of health of 8.53 (SD = 0.92). Median measured near visual acuity was 20/20 in the younger adults and 20/30 in the older adults. Participants received a stipend of $15 USD for participation. All participants had normal color vision, by self-report.

Tasks and Procedures

The tasks and procedures were very similar to those of Experiment 1 with the important exception that the saccade response modality was replaced by a body-tilt response. The participant viewed the display while standing, with the center of the monitor adjusted to eye level. In response to the rotation of the photograph, the participant was instructed to “shift your weight and tilt slightly in the same direction as the picture” and to do this as quickly as possible without making mistakes. Muscle activity was sensed by three electrodes placed on the thigh of the dominant leg. One electrode was placed over the head of the gastrocnemius muscle, 5 cm below the bend of the knee; the second electrode was placed over the belly of the muscle; the third reference electrode was placed 5 cm medially from the second. To help maintain balance throughout the experiment, the participant held on to a grab bar mounted crosswise on a table at waist height. Offline, the time from the appearance of the rotated photograph to the onset of muscle movement was obtained. The experimenter noted the direction of the tilt from the continuous record and entered that using the keyboard.

The types and numbers of trials were as in Experiment 1.

Results

Analyses of variance were carried out on the mean dual-task RTs for trials on which both responses were correct (resulting in the loss of 3% of the trials) and on the proportion correct. Age group (younger or older) was a between-subjects factor. Response modality (body tilt or keypress) and SOA (50, 100, 150, 200, 500, and 1,000 ms) were within-subjects factors. Tests for sphericity were carried out and, where significant, the Geisser-Greenhouse corrected probabilities are reported.

Color dual task (Task 1) RT. There was a significant main effect of age group, $F(1, 31) = 37.98$, $p < .001$, $\eta_p^2 = .55$, with older adults (M = 742 ms, SE = 32 ms) slower than younger adults (M = 467 ms, SE = 31 ms). There was also a significant effect of SOA, $F(5, 155) = 21.44$, $p < .001$, $\eta_p^2 = .41$. Follow-up tests showed that RTs were higher at SOAs of 50 ms, 500 ms, and 1,000 ms (M = 638 ms) than at intermediate SOAs (M = 571 ms).

Color dual task (Task 1) proportion correct. Accuracy was higher in older adults (M = 0.99, SE = 0.01) than in younger adults (M = 0.97, SE = 0.01), $F(1, 31) = 4.63$, $p = .040$, $\eta_p^2 = .14$. There was also a significant interaction of age group and response modality, $F(1, 31) = 5.49$, $p = .026$, $\eta_p^2 = .16$. Older adults were equivalent in body tilt (M = .99, SE = .01) and keypress (M = .98, SE = .01) whereas younger adults were less accurate in body tilt (M = .96, SE = .01) than in keypress (M = .98, SE = .01).

Rotation dual task (Task 2) RT. There was a significant main effect of age group, $F(1, 31) = 44.12$, $p < .001$, $\eta_p^2 = .59$, with older adults (M = 738 ms, SE = 25 ms) slower than younger adults (M = 510 ms, SE = 24 ms). There was also a significant main effect of SOA, $F(5, 155) = 92.95$, $p < .001$, $\eta_p^2 = .75$, with RTs decreasing from 50-ms SOA (M = 737 ms, SE = 21 ms) to 1,000-ms SOA (M = 517 ms, SE = 13 ms). The main effect of modality was not significant, $F(1, 31) = 1.14$, $p = .294$, $\eta_p^2 = .04$. There was a significant interaction of age group and response modality, $F(1, 48) = 6.19$, $p = .018$, $\eta_p^2 = .17$. Younger adults responded more quickly with a keypress (M = 495 ms, SE = 30 ms) than with a body tilt (M = 525 ms, SE = 26 ms) whereas older adults responded more quickly with a body tilt (M = 700 ms, SE = 27 ms) than with a keypress (M = 776 ms, SE = 31 ms). The PRP effect was larger for older adults (M = 299 ms, SE = 24 ms) than for younger adults (M = 140 ms, SE = 23 ms), as evidenced by the significant interaction between age group and SOA, $F(5, 155) = 12.07$, $p < .001$, $\eta_p^2 = .28$. There was also an interaction of response modality and SOA, $F(5, 155) = 22.71$, $p < .001$, $\eta_p^2 = .21$. The PRP effect was smaller with a body tilt (M = 145 ms, SE = 18 ms) than with a keypress (M = 294 ms, SE = 22 ms). The three-way interaction of age group with response modality and SOA was not significant, $F(5, 155) < 1$. The interaction of response modality and SOA is shown separately for younger and older adults in Figure 3.

Rotation dual task (Task 2) proportion correct. There were no significant effects. Accuracy was equivalent in younger and older adults ($M = 0.99$, $SE = 0.01$).

Discussion

For the older adults, the RTs to Task 2 follow the pattern predicted by the engage-bottleneck-later model: Replacing the stimulus-response-compatible keypress with the ideomotor-compatible body tilt significantly reduced the PRP effect. This was predicted if aspects of selecting and implementing the body-tilt response could begin before Task 1 central processing was complete and the bottleneck opened. The results for the younger adults appear problematic. The body-tilt response was harder—resulted in a longer RT—than the keypress response at long SOAs. As the SOA was reduced, the effect of that greater difficulty was reduced. Recall that the RSB model predicts such subadditive effects when the difficulty of early perceptual processing in Task 2 is increased; the effect of the increased difficulty is absorbed in the cognitive slack that results from waiting for the bottleneck to open. One interpretation, then, is that some aspect of response selection for the body tilt task was able to move forward past the bottleneck into the early, perceptual stage of processing. Were this possible, it seems likely it would also have been seen with the saccade task in Experiment 1.

Moreover, the manipulation here was not of perceptual processing—of the stimulus—but of the response required. In fact, the subadditive interaction that was seen is consistent with the engage-bottleneck-later model. Figure 4 shows the predictions of the model for three cases: (a) Task 2 with a tilt response is harder than Task 2 with a keypress at long SOAs, (b) Task 2 with a tilt response is equivalent in difficulty to Task 2 with a keypress at long SOAs, and (c) Task 2 with a tilt response is easier than Task 2 with a keypress at long SOAs. As can be seen, the subadditive

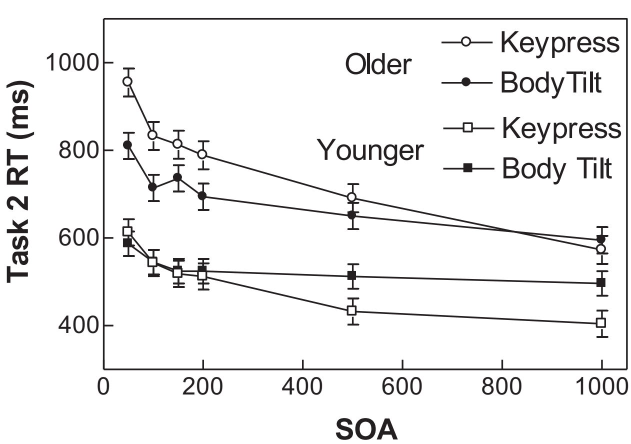

Figure 3. Reaction times (RTs) to rotation task (Task 2) showing interaction of stimulus onset asynchrony (SOA) with response modality (body tilt or keypress responses) for younger adults and older adults in Experiment 2.

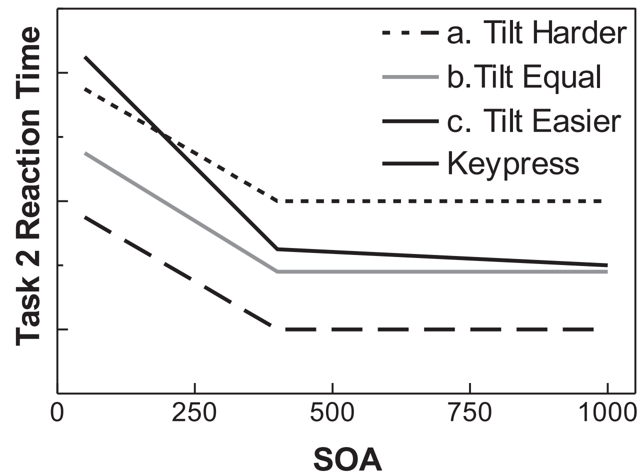

Figure 4. Predictions of the engage-bottleneck-later model for Task 2 RT as a function of stimulus onset asynchrony (SOA) in three cases: Tilt response is harder than keypress response at long SOAs (a); tilt response is equivalent in difficulty (b); tilt response is easier (c).

results for younger adults are consistent with the predictions for the case in which Task 2 is harder than Task 1 at long SOAs. The results for the older adults are consistent with the predictions for the case in which the two tasks are equally difficult at long SOAs. The difference may come because older adults have more experience in conscious adjustments of body position since effort is called for to maintain posture and balance. Nevertheless, for both age groups, certain aspects of response selection must be able to escape the bottleneck, whereas others must not, as evidenced by the nonzero PRP effects.

It is interesting to note that for the older adults, the RTs with the keypress and tilt responses were equivalent at the longest SOA. This suggests that the apparent bypass is not due to lower task difficulty but is rather due to the ideomotor-compatible nature of the task.

As with Experiment 1, there are reasons to question the connotative definition of ideomotor compatibility. The stimulus is not identical to the sensorimotor feedback after the response of a body tilt; in fact, the effect of a body tilt is to bring the stimulus back into upright orientation with respect to the plane of the body.

General Discussion

In the engage-bottleneck-later model, which is a modified version of the response-selection bottleneck model, the central processing of Task 2 can begin before central processing of Task 1 is complete, partially bypassing the normal bottleneck that prevents simultaneous central processing for two tasks (Lien et al., 2005b). The signature for this partial bypass is that the slowing of the RT to Task 2 as the SOA decreases is reduced, resulting in a smaller PRP effect. Complete bypass would be signaled by the absence of a PRP effect. Relative to conditions in which Task 2 was merely stimulus-response compatible, younger and older adults in both experiments showed the reduced PRP effects that are evidence for partial bottleneck bypass in ideomotor-compatible conditions. Neither group showed perfect timesharing—an absence of a PRP effect—of the kind Greenwald had found (Greenwald, 1972, Greenwald & Shulman, 1973). They did show the partial bottleneck bypass with ideomotor-compatible stimuli for Task 2 as Lien et al. (2005b) found. Greenwald used a 0-ms SOA and blocked those trials; simultaneous responding to the two tasks was also emphasized. Lien et al. used a PRP procedure with SOAs varying within blocks, as was used in the present experiments.

The qualitative equivalence of the younger and older adults in the present experiments is in contrast with the qualitative difference seen in studies of training in the PRP procedure. In prior research, as many as 85% of younger adults showed bottleneck bypass after thousands of trials of practice on Task 2 (Maquestiaux et al., 2008), whereas after as many as 10,000 trials of training, at most 20% of older adults showed some evidence for bypass (Maquestiaux et al., 2013). In those experiments, after training, Task 1 was a novel, previously untrained stimulus-response pairing, and there was neither stimulus-response nor ideomotor compatibility. Strobach et al. (2012b) reported evidence consistent with bottleneck bypass after extensive training but used simultaneous presentation of the tasks rather than the PRP procedure used here and by Maquestiaux et al. (2010, 2013). The present experiments, on the other hand, showed evidence of bottleneck bypass without extensive training. The critical difference from the prior studies would appear to be the use of ideomotor-compatible procedures for Task 2.

Here it might be argued in Experiment 1 that a saccade to a peripheral target is not only ideomotor compatible but also is reflexive or is at least a previously learned and very highly practiced response throughout life, and this is what allowed older adults to bypass. Yet a body tilt toward a rotated stimulus is a novel and unpracticed pairing, is ideomotor-compatible, and is apparently not reflexive, and still older adults showed evidence of bypass. We can conclude that ideomotor-compatible stimulus-response combinations allow partial bottleneck bypass, and that capability is preserved in old age.

The amount of bottleneck bypass is reflected in the reduction in the PRP effect from the keypress condition to the ideomotor-compatible conditions. Across the two experiments, the PRP effect in the keypress condition was 269 ms; the PRP effect for body tilt was 145 ms; the PRP effect for saccades was 73 ms. The strong reflexive component of the saccade response in the direction of peripheral movement likely accounts for the greater bypass than body tilt, which we argued was not reflexive. This raises the question of why body tilt leads to bypass relative to the stimulus-response compatible keypress response. We argued earlier that the reflexive response to a tilt in the visual world would be a body tilt in the opposite direction. This would be the reflexive response to a change in balance. Here, however, the rotation of the stimulus did not cause any change in balance; it led to a change in the orientation of the visual display, which was quite large, extending about 17 deg into the periphery. There may in fact exist a reflexive tendency to align the midline of the body with the orientation of the visual world, to maintain the original orientation of the frame. Unlike a saccade, however, tilting the body requires complex coordination of a larger number of muscle groups with the result that there is less benefit from the reflexive tendency.

Next, we revisit the concept of ideomotor compatibility. Recall that the connotative definition of ideomotor compatibility is that the sensory feedback from the response is identical to the stimulus (Greenwald, 1972). An example of this is the response of saying a word in reaction to the stimulus of hearing the word. The response representation is directly activated by the stimulus. We noted previously that the stimuli and responses in the present experiments did not satisfy that definition. The denotative definition of ideomotor compatibility comprises the combinations of stimuli and responses that have given evidence of bottleneck bypass. It is useful to review combinations that are and are not presumptively ideomotor compatible. Saying "left" or "right" in response to the auditorally presented words "left" or "right" (or "A" or "B" in response to "A" or "B") is ideomotor-compatible, but saying "left" or "right" in response to "one" or "two" (or "1" or "2" in response to "A" or "B") is not (Greenwald, 1972, 2003; Lien et al., 2002; Lien et al., 2005b). A saccade to a peripheral target is ideomotor-compatible, but a saccade whose direction is determined by a color patch at fixation is not (Pashler et al., 1993; cf. the present Experiment 1). Moving a joystick left or right or responding with the left or right index finger in response to a left-pointing or right-pointing arrow is ideomotor-compatible, but a similar response to "A" or "H" presented auditorally or to "left" or "right" either visually or auditorally presented is not (Greenwald, 1972; Greenwald & Shulman, 1973; Lien et al., 2002; Lien et al., 2005b). It appears not to matter whether the directional arrow is at fixation (Lien et al., 2002) or in the left or right periphery consistent with the arrow direction. Finally, in the present Experiment 2, a body tilt in the direction of peripheral visual change appeared ideomotor compatible, whereas a keypress with the left or right of two fingers on the same hand did not.

These examples appear to fall into two classes. The first class involves simply verbally shadowing an auditory stimulus. Consistent with the connotative definition, no look up of the stimulus-response mapping is required; the stimulus contains the response rule. It may well be that hearing a word automatically activates the articulatory programming to say it. These arguments do not apply to the second class, directional visual stimuli. Such stimuli—either abrupt onsets or directional indicators—result in very rapid shifts of attention to the location of the onset (e.g., Remington, Johnston, & Yantis, 1992) or the location indicated (e.g., Jonides, 1980). We propose that this shift of attention is more rapid even than a saccade and that it is immune to the response-selection bottleneck. Although the stimulus gives some indication of the direction of the required response, the preparation of the motor response may still require additional, possibly conscious, processing, and that processing may be subject to the response-selection bottleneck. Such a two-part mechanism would explain both why some bypass occurs, and why the PRP effects do not disappear completely. We suggest that lumping these two classes—auditory shadowing and cued spatial direction—together under the single rubric of ideomotor compatibility has obscured the fact that they do not share the same underlying mechanism. From this perspective, older adults benefitted from cued spatial direction in the same way as did younger adults. There is little evidence for age-related differences in basic mechanisms of focusing and shifting attention (Hartley, 1992; Kramer & Madden, 2008). It remains to be seen whether older adults will show bypass with auditory shadowing as Task 2, although it seems likely they will.

A shift in attention is not, alone, sufficient to explain the ideomotor-compatibility effect. The response must be such that it can capitalize on the shift. We speculate that body movement in the direction of an attention shift in general has a reflexive component and that the complexity and degree of coordination required for a movement governs the magnitude of the compatibility effect. We propose, that is, that the ideomotor-compatibility effect arises from the at-least-partially reflexive nature of the response to an attention shift. From this perspective, movement of a joystick left or right in response to a shift of attention to the corresponding periphery should also produce a reduction in the PRP effect. The reduction might be intermediate between saccades and body tilts because movement of a joystick requires more coordination than a saccade and less than a tilt of the whole body. The present results suggest these considerations—attentional shifts facilitating reflexive responses—apply equally to younger and older adults. We can conclude that ideomotor-compatible stimulus-response combinations allow partial bottleneck bypass, and that capability is preserved in old age.

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