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Effects of Aging on Externally Cued and Internally Driven Uncertainty Representations

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Objective: The Hick–Hyman law states that response time (RT) increases linearly with increasing information uncertainty. The effects of aging on uncertainty representations in choice RT paradigms remain unclear, including whether aging differentially affects processes mediating externally cued versus internally driven uncertainty. This study sought to characterize age-related differences in uncertainty representations using a card-sorting task. ***Method:*** The task separately manipulated internally driven uncertainty (i.e., probability of each stimulus type with fixed number of response piles) and externally cued uncertainty (i.e., number of response piles with fixed probability of each stimulus type). ***Results:*** Older adults (OA) showed greater RT slowing than younger adults in response to uncertainty load, an effect that was stronger in the externally cued than internally driven condition. While both age groups showed lower accuracy and greater RTs in response to unexpected (surprising) stimuli in the internally driven condition at low uncertainty loads, OA were unable to distinguish between expected and nonexpected stimuli at higher uncertainty loads when the probability of each stimulus type was close to equal. Among OA, better performance on the internally driven, but not externally cued, condition was associated with better global cognitive performance and verbal fluency. ***Conclusions:*** Collectively, these findings provide behavioral evidence of age-related disruptions to bottom-up (externally cued) and top-down (supporting internally driven mental representations) resources to process uncertainty and coordinate task-relevant action.

Key Points

Question: This study examined the effects of healthy aging on externally cued and internally driven representations of uncertainty, which may be associated with bottom-up and top-down processing, respectively. ***Findings:*** Older adults showed disruption to both externally cued and internally driven uncertainty representations. ***Importance:*** Findings suggest that older adults have disruptions to both bottom-up and top-down resources to process uncertainty and coordinate task-relevant action. ***Next Steps:*** Future studies should investigate the neural mechanisms of uncertainty representations and use this paradigm in the context of neurodegenerative conditions affecting cognitive control networks.

Keywords: Hick–Hyman law, choice uncertainty, uncertainty representation, posterior-to-anterior shift in aging, healthy aging

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The mathematical framework of information theory quantifies the processing and utilization of information, which is specified as that which reduces entropy or uncertainty in a given process (Shannon, 1948). In the psychological sciences, a classic series of experiments demonstrated that response time (RT) increases linearly with increasing information uncertainty, an effect known as the Hick–Hyman law (Hick, 1952; Hyman, 1953). Studies of the Hick–Hyman law use choice RT tasks that vary information uncertainty at the level of either the stimulus or the required response (see Proctor & Schneider, 2017, for review). The average amount of uncertainty

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(H) in a choice RT task can then be computed as $-\Sigma p(i)\log_2 p(i)$, where $p(i)$ is the probability of each choice alternative and $\log_2 p(i)$ is the informational value or "surprisal" of each choice alternative as expressed in bits. Thus, H equals the weighted average of the uncertainty involved in the set of individual alternative events expressed in bits of information and the time it takes to make a response within a choice RT task increases with the average amount of uncertainty.

Healthy cognitive aging has previously been found to negatively affect an individual's response to information uncertainty (Eppinger & Kray, 2011; Pietschmann et al., 2011). When performing probabilistic reward learning tasks, for example, older adults (OA) show a deficit in uncertainty-driven learning (Nassar et al., 2016), do not accurately estimate the changeability of task states (Hämmerer et al., 2019), and show a preference for certainty of sure gains and avoidance of sure losses (Mather et al., 2012). However, while probabilistic learning tasks manipulate one type of uncertainty (i.e., the uncertainty of receiving a reward following a response on a given trial), these tasks differ from choice RT tasks that parametrically vary either the number of response options or the probability of a specific stimulus appearing. Although one small choice RT study ($N = 10$ young adults [YA] and $N = 14$ OA) showed that OA had steeper RT slopes with increasing uncertainty load, consistent with the Hick–Hyman Law (Sleimen-Malkoun et al., 2013), a recent review of Hick's law described no additional studies examining the law in the context of healthy aging (Proctor & Schneider, 2017). Thus, the nature of aging effects on uncertainty representations in the context of choice RT paradigms in the absence of explicit probabilistic rewards remains unclear.

In particular, it is not known whether healthy aging differentially affects processes mediating externally cued versus internally driven uncertainty. Externally cued uncertainty (e.g., differences in the number of equally likely choice alternatives) places less demands on internal representations of uncertainty and response preparation, but greater demands on bottom-up perceptual resources as individuals employ a "search-and-match" process to iterate through response options—with greater processing then required as the number of choices increases. In contrast, internally driven uncertainty (e.g., differences in the probability of occurrence of a fixed number of choice options) places greater demands on top-down executive control processes, as it requires a person to develop internal representations of uncertainty for each possible response option. To date, no studies have directly compared these two types of uncertainty in the context of healthy cognitive aging or examined trial-level response patterns such as stimulus expectancy (surprisal) in this type of choice RT paradigm.

Brain imaging studies in YA point to the role of the prefrontal cortex, and more specifically the cognitive control network (CCN), in mediating the brain's ability to represent and resolve uncertainty (Fan, 2014; Fan et al., 2014; Nassar et al., 2019; Wu et al., 2018). For example, a functional magnetic resonance imaging study by Wu et al. (2018) used a paradigm in which number of response alternatives (arrow directions) and type of response required (reversed or nonreversed) varied between conditions, permitting a dissociation of uncertainty type associated with stimulus representations versus response generation. They reported that the CCN, including anterior cingulate cortex, frontal eye fields, midfrontal gyrus, anterior insula, and intraparietal sulcus, mediated the relationship between uncertainty and RT. While both the CCN and default mode network were associated with uncertainty representation, only the CCN was additionally involved in response generation as indexed by neural activation associated with trial-by-trial RT, controlling for total entropy (uncertainty). Other work has demonstrated that the CCN is particularly activated when presented with low-probability, surprising stimuli (De Baene & Brass, 2013; Niendam et al., 2012; Wu et al., 2021), suggesting that this network may be important for the processing of internally driven representations of the overall context of a sequence of events as well as information conveyed by specific event types. To date, however, no known neuroimaging studies have specifically compared externally cued and internally driven uncertainty representations.

A robust body of work demonstrates an age-related shift in neural activity in OA, with a reduction in activity in posterior regions along with a commensurate increase of activity in anterior regions including within the CCN (Ballesteros et al., 2015; Davis et al., 2008; McCarthy et al., 2014; Zhang et al., 2017). For example, OA demonstrate higher functional connectivity between the anterior cingulate cortex, anterior insula, and inferior frontal gyrus (Cao et al., 2014) than YA, which may be a response to disrupted white matter connectivity in long-range tracts connecting frontoparietal regions (Xia et al., 2022). Although this posterior-to-anterior shift in aging has typically been conceptualized as a compensatory response, recent work suggests that it may better reflect a loss of neural efficiency, functional specificity, or neural adaptation (see Myrum, 2019, for review). This body of neuroimaging research is also supported by behavioral studies suggesting that age-related disruption of bottom-up perceptual resources mediated by posterior regions may contribute to a bias toward top-down processing mediated by anterior resources (Açık et al., 2010; Festa et al., 2017; Lai et al., 2020; Li et al., 2013; Ramzaoui et al., 2021; Zhuravleva et al., 2014). To the extent that externally cued uncertainty places greater demands on bottom-up perceptual processing while internally driven uncertainty places greater demands on top-down processes that monitor and coordinate responses to internal uncertainty representations (Proctor & Schneider, 2017), this bias toward top-down processing may therefore lead to differentially greater impairment in processing externally cued than internally driven uncertainty in OA. The ability to separately examine externally cued and internally driven uncertainty representations within a choice RT paradigm may therefore provide a unique window into the dynamics of bottom-up and top-down processing during aging.

We previously investigated the effects of Alzheimer's disease (AD) on the ability to process and respond to uncertainty (Korthauer et al., 2019) and found that AD patients were selectively impaired under internally driven, but not externally cued uncertainty conditions compared to healthy OA. Moreover, consistent with a critical role of executive control processes in the internal representation of uncertainty, RT in the internally driven condition was also found to be specifically associated with neuropsychological measures of executive functioning, but not episodic memory. However, our previous work did not include a healthy younger comparison group that allowed us to address how normal aging affects the representation and resolution of uncertainty. The purpose of the present study was therefore to investigate the effects of healthy cognitive aging on externally cued and internally driven representations of uncertainty. This study made several important methodological improvements to previous studies: (a) a within-subjects design permitted direct comparison of the externally cued and internally driven conditions; (b) the amount of information (uncertainty) was matched for low, medium, and high load blocks within each condition; and (c) quantification of trial-level RT permitted separate analysis of

unexpected (surprising) stimuli, providing an index of internally driven uncertainty representations.

We made several predictions regarding the effects of healthy aging on the processing of uncertainty. First, we hypothesized that given age-related disruptions to bottom-up perceptual resources and top-down cognitive control, OA would show greater sensitivity to both externally cued and internally driven uncertainty, indicated by steeper RT slopes with increasing uncertainty load as compared to YA. Second, given the shift to increased activity within anterior brain regions and reduced activity within posterior brain regions displayed by OA, we also predicted that this age-related increase in sensitivity may be greater for externally cued than internally driven uncertainty. Third, we predicted that OA would show disrupted internal representations of uncertainty as indexed by their responses to expected versus unexpected (surprising) stimuli in the internally driven uncertainty condition. Last, we conducted exploratory analyses to determine whether there were associations between choice RT and performance on conventional neuropsychological tests. Consistent with the role of frontal networks including the CCN in processing internally driven uncertainty and our previous findings with AD patients, we hypothesized that performance in the internally driven condition would be associated with tests of executive functioning.

Method

Participants

Cognitively normal, English-speaking younger adult (YA; $N = 36$; $M_{\text{age}} = 19.14$ years [$SD = 1.13$; range 17–22]; M education = 13.0 years [$SD = 1.3$; range 12–16]; 75% women; 42% non-Hispanic White, 33% Asian, 17% Hispanic/Latino, 6% Black, 3% other) and OA ($N = 40$; $M_{\text{age}} = 73.35$ years [$SD = 6.88$; range 59–87]; $M_{\text{education}} = 15.9$ years [$SD = 2.5$; range 12–23]; 70% women; 88% non-Hispanic White, 3% Black, 10% other; M Mini-Mental Status Examination, MMSE = 29.0 years [$SD = .95$; range 27–30]) with normal or corrected-to-normal vision were recruited from Brown University. YA had significantly fewer years of education than OA, $t(75) = 2.93$, $p < .001$, consistent with their status as current college students. Exclusion criteria included a history of learning disabilities, serious neurologic or psychiatric illness, prior diagnosis of mild cognitive impairment or dementia, and MMSE score < 26 (for OA, no participants excluded for low MMSE score). No participants were excluded based on performance on the uncertainty tasks. This study was approved by the Brown University's Institutional Review Board, and all participants provided written informed consent in accordance with the principles of the Declaration of Helsinki.

Procedure

The externally cued and internally driven uncertainty tasks were presented on a 24-in. Dell monitor (screen resolution: 1,920 × 1,200 pixels; refresh rate: 60 Hz) at a viewing distance of approximately 50 cm. The tasks were programed using E-Prime 2.0 software Psychology Software Tools, Pittsburgh, PA (Psychology Software Tools, 2012). Test stimuli consisted of five rectangular cards, each with a different black outline of a geometric shape (Figure 1). The background color of the cards differed between each sorting condition (i.e., blue, green, orange) to reinforce the different probability structures of the sorting decks across trial blocks. On each trial, a target card appeared at the bottom of the screen. Participants were instructed to sort the card by matching its shape to one of the response piles at the top of the screen. The response piles were labeled by a reference card with the same shape as one of the possible stimulus cards. No cues were provided to indicate the size of the response piles as participants sorted cards, ensuring that they relied on internal representations of the deck's stimulus probability structure rather than external cues of response pile size. Participants responded by pressing one of five buttons on the Serial Response Box (Psychology Software Tools, 2012), followed by a 1-s intertrial delay. They were instructed to respond as quickly and accurately as possible and maintain the same finger-response key mapping throughout the task. Each block of trials consisted of a single stimulus deck of 60 cards presented in pseudorandom order. All participants completed the externally cued task before the internally driven task. This served as additional training for stimulus–response mapping of button presses. Because each stimulus occurred equally often in the externally cued task, stimulus–response mapping was well established before participants completed the internally driven task in which stimuli occurred unequally. The entire task took an average of 25 min.

Externally Cued Uncertainty Task

Participants completed three sorting conditions in which the total number of response piles varied from three to five. These piles provided an external cue regarding the stimulus–response uncertainty, with conditions corresponding to 1.6, 2.0, and 2.3 bits of uncertainty (H), per the formula $H = \log_2(n)$, where n = number of piles (Shannon, 1948). Participants completed five practice trials for the five-pile condition prior to beginning the task. The order of the conditions (number of response piles) was counterbalanced across participants.

Internally Driven Uncertainty Task

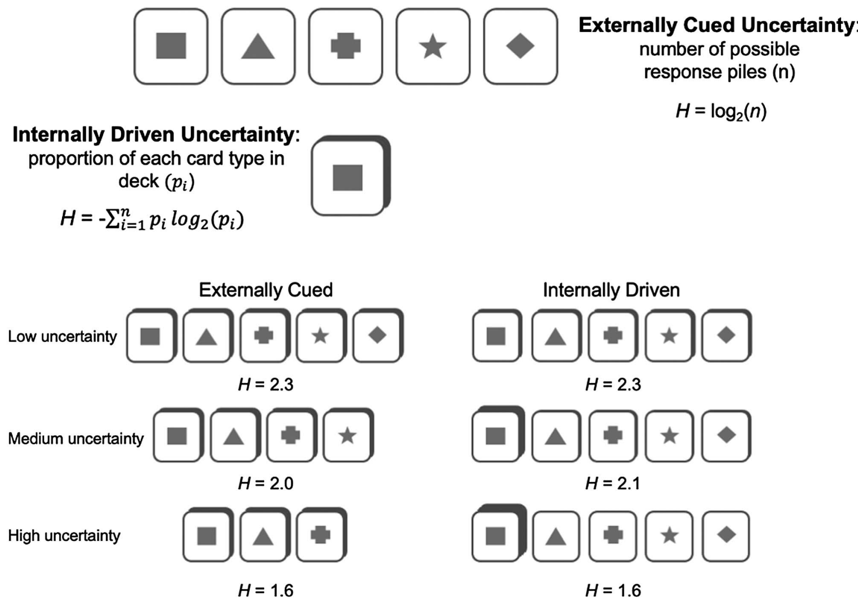
Participants completed three sorting conditions in which the number of response piles was fixed at five piles (corresponding to the five potential shapes). The probability structure of each deck (i.e., the probability of each stimulus type occurring) varied across conditions. Because the number of response piles was fixed, there were no external cues regarding uncertainty within each condition; rather, uncertainty was internally driven based on the frequency of occurrence for each stimulus type. A load of information uncertainty was matched to the externally cued uncertainty task, with 1.6, 2.1, and 2.3 bits of information, per the following formula:

$$H = -\sum_{i=1}^{n} p_i \log_2(p_i), \quad (1)$$

where p_i = probability of each of the possible types of trials and n = number of piles (fixed at 5; Shannon, 1948). This corresponded to the following three sorting conditions: (a) 66.7% of one card type, 8.3% of the other four card types; (b) 46.7% of one card type, 13.3% of the others; (c) 26.7% of one card type, 18.3% of the others. At the medium uncertainty load, H was 2.0 bits for the externally cued condition and 2.1 bits for the internally driven condition, as precise matching was not possible within a 60-card deck. At the high uncertainty load, $H = 2.3$ bits and $n = 5$ cards for both the externally cued and internally driven conditions, but the card probabilities differed in the internally driven condition in order to preserve the comparison between expected and

Figure 1

Paradigm Manipulating Externally Cued and Internally Driven Uncertainty



Note. The paradigm was a choice reaction time card-sorting task that separately manipulated externally cued uncertainty (i.e., number of response choices) and internally driven uncertainty (probability structure of the stimulus card deck). Participants completed blocks of trials in which they were instructed to sort the top card in the stimulus deck into its corresponding response pile. They were instructed to respond as quickly as possible while remaining as accurate as possible.

unexpected cards in that condition. The stimulus that occurred most frequently was pseudorandomly chosen for each sorting condition and counterbalanced across participants. The order of the three sorting conditions was counterbalanced across participants.

Neuropsychological Assessment

OA completed a brief neuropsychological battery, which assessed the domains of global cognition (Mini-Mental Status Examination, Folstein et al., 1975; Repeatable Battery for the Assessment of Neuropsychological Status Total Score, Randolph et al., 1998), attention (Wechsler Adult Intelligence Scale–IV Digit Span, Wechsler, 2008), psychomotor speed (Trail-Making Test A, Reitan, 1992), and executive functioning (Trail-Making Test B, Delis–Kaplan Executive Function System [DKEFS] Letter Fluency, Category Fluency, and Category Switching; Delis et al., 2001). Due to time constraints for testing of the YA, who received course credit for their participation, and the likelihood of observing restricted performance ranges in this age group, we did not include neuropsychological assessment for this group.

Sample Size Determination

In our prior study examining uncertainty representations in AD patients (Korthauer et al., 2019), cognitively unimpaired OA showed large differences between externally cued and internally driven uncertainty (Cohen's $d = 1.1$) using a between-subjects design. A power analysis (IBM SPSS 27) found that a sample size of $N = 11$ would detect a similar effect at 90% power with a within-subjects design. However, because we additionally sought to examine the effects of stimulus expectancy, which we expected to be a less robust effect, particularly at higher uncertainty loads, we powered the study to detect a medium-sized effect ($d = 0.5$) at 90% power ($N = 40$ per group).

Data Analysis

For both tasks, RT for each trial (regardless of correct or incorrect response) was recorded and averaged across each block of trials for a given stimulus deck. Trials with RTs >2,500 ms were considered outliers and likely reflected inattentiveness to the task. The total number of trials excluded was small (average of 0.9%; no more than 5% of trials for any given participant) and did not differ across the groups (YA: 1.0%, OA: 0.9%). The average RT within each block was the primary dependent variable. Accuracy was calculated for each block of trials. The slope of a best-fit line between uncertainty load and RT was calculated for each participant. For the internally driven condition in which the probability structure of the card deck differed by block, we calculated the mean RT for expected and unexpected cards within each condition.

Mean accuracy was quite high for all conditions (average >96% across uncertainty loads for each group), causing statistical assumptions of normality to be violated. Thus, nonparametric statistics (Mann–Whitney U tests for between-group comparisons and Wilcoxon signed-rank tests for paired samples) were used to test differences in accuracy. For RT, an omnibus generalized linear model (GLM) was used with uncertainty condition (externally cued, internally driven), uncertainty load (low, medium, high), and group

(YA, OA) as predictor variables and RT as the outcome variable of interest. To facilitate the interpretation of three-way interactions, separate GLMs were then constructed for YA and OA, with uncertainty load (low, medium, high) and condition (externally cued, internally driven) as predictors. Paired t tests were used for post hoc comparisons of significant interaction effects. For the internally driven condition in which one card type occurred more frequently than the others, we also constructed GLMs to test the effect of card expectancy on RT, with uncertainty load (low, medium, high), card expectancy (unexpected, expected), and group (YA, OA) as predictor variables. Significant three-way interactions were followed by separate GLMs for YA and OA. For all GLMs, Mauchly's test was used to determine whether the sphericity assumption was violated. Where sphericity was violated, the Greenhouse–Geisser correction was used. A statistical significance threshold of $\alpha < .05$ was used for all statistical tests. Effect sizes are reported as estimates of partial eta squared (η^2).

Transparency and Openness

We have reported how we determined our sample size, all data exclusions, and all measures in the study. Materials and analysis code are not publicly available but may be shared upon reasonable request to the study authors. All analyses were conducted using SPSS Version 27 (IBM; Armonk, New York). The study's design and its analysis were not preregistered.

Results

Group Differences in Externally Cued and Internally Driven Conditions

Mean accuracy was high for the externally cued (>96% across uncertainty loads and groups) and internally driven conditions (>97%; Table 1). Nonparametric Mann–Whitney U tests showed a significant group difference at all uncertainty loads on the internally driven condition and at the lowest uncertainty load for the externally cued condition ($ps < .05$). OA had higher accuracy than YA for all of these comparisons.

For RT, the three-way (Uncertainty Condition × Uncertainty Load × Group) interaction was significant, $F(2, 148) = 9.93$, $p < .001$, $\hat{\eta}^2 = .12$, as were all of the two-way interactions ($ps < .001$) and the main effects of load, uncertainty condition, and group ($ps < .001$). The main effect of group, $F(1, 74) = 192.33$, $p < .001$, $\hat{\eta}^2 = .72$, showed the expected age-related RT slowing in OA compared to YA. Other two-way interactions and main effects were explored by disentangling the three-way interaction by conducting separate GLMs for YA and OA. YA showed a significant main effect of load, $F(2, 70) = 126.15$, $p < .001$, $\hat{\eta}^2 = .78$, but no main effect of uncertainty condition, $F(1, 35) = .004$, $p = .95$, $\hat{\eta}^2 < .001$ (Figure 2). OA showed a main effect of load, $F(1.7, 78) = 106.59$, $p < .001$, $\hat{\eta}^2 = .73$, a main effect of uncertainty condition, $F(1, 39) = 50.63$, $p < .001$, $\hat{\eta}^2 = .57$, and a Load × Uncertainty Condition interaction, $F(2, 78) = 24.32$, $p < .001$, $\hat{\eta}^2 = .38$. Post hoc paired-samples t tests showed no difference in RT between externally cued and internally driven uncertainty at the lowest load, $t(39) = 1.04$, $p = .30$, Hedges' $g = .13$, whereas RT was significantly slower in the externally cued condition for medium, $t(39) = 3.74$, $p = .001$, Hedges' $g = .49$, and high loads, $t(39) = 10.38$, $p < .001$, Hedges' $g = 1.03$.

Table 1
Mean Accuracy by Condition and Uncertainty Load

Uncertainty condition	YA % (*SD*)	OA % (*SD*)	Mann–Whitney *U*
Externally cued			
Low uncertainty	97.2 (2.4%)	98.7 (1.2%)	1180.5**
Medium uncertainty	96.9 (2.5%)	97.8 (1.6%)	1035.0
High uncertainty	96.7 (2.1%)	96.9 (2.2%)	886.5
Internally driven			
Low uncertainty	97.3 (2.0%)	99.1 (0.9%)	1331.5***
Medium uncertainty	96.7 (2.5%)	98.4 (1.5%)	1177.5**
High uncertainty	96.4 (2.1%)	97.7 (1.4%)	1119.0*

Note. YA = younger adult; OA = older adult. Due to the high overall accuracy that restricted the range and caused a left skew in the distribution, nonparametric Mann–Whitney U tests were performed to compare YA and OA. Overall, OA showed higher accuracy than YA at all internally driven uncertainty loads and the lowest externally cued uncertainty load.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Differences in slopes of the linear fit between uncertainty and RT were assessed via a two-way (Uncertainty Condition × Group) repeated measures analysis of variance. There was a significant main effect of group, $F(1, 74) = 53.61$, $p < .001$, $\hat{\eta}^2 = .42$, with OA having significantly steeper slopes than YA, indicating greater RT slowing as uncertainty load increased. There was a significant main effect of condition, $F(1, 74) = 52.42$, $p < .001$, $\hat{\eta}^2 = .42$, with groups having steeper slopes for the externally cued than internally driven condition. The Condition × Group interaction was also significant, $F(1, 74) = 21.06$, $p < .001$, $\hat{\eta}^2 = 22$, with OA having a greater magnitude of difference in slopes between externally cued and internally driven than did YA (Figure 3).

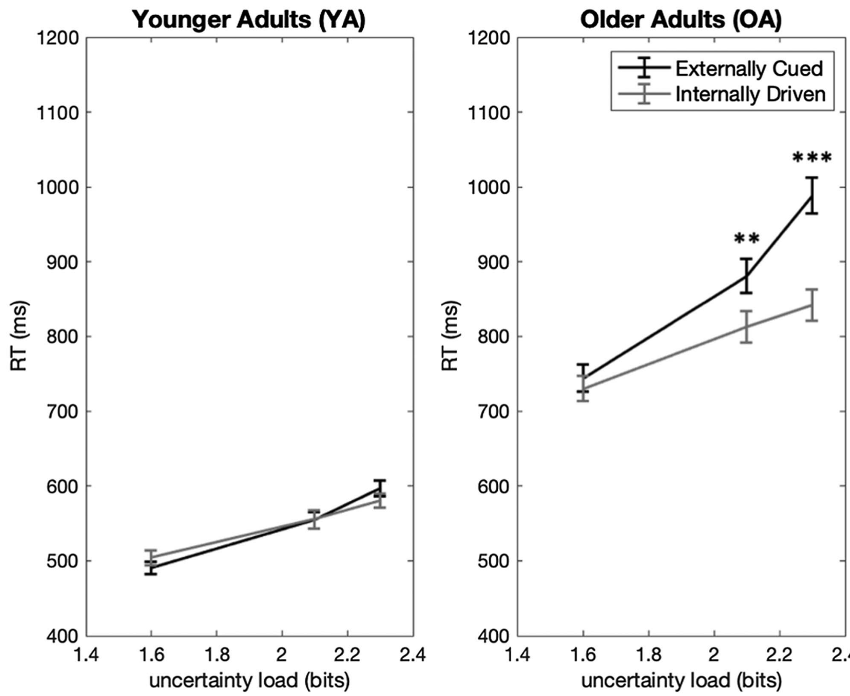
Group Differences by Card Expectancy in Internally Driven Condition

Faster and more accurate responses to expected compared to unexpected cards in the internally driven condition are an index of a participant's ability to learn the probability structure of the card deck. Nonparametric Wilcoxon signed-rank tests showed that both groups had higher accuracy for expected than nonexpected cards at low and medium uncertainty loads ($ps < .05$), but only YA showed a difference in accuracy at the highest uncertainty load ($p < .05$; Table 2).

For RT in the card expectancy analysis, there was a significant Load × Card Expectancy × Group interaction, $F(2, 73) = 5.33$, $p = .01$, $\hat{\eta}^2 = .13$. For YA, follow-up tests showed a significant Load × Expectancy interaction, $F(2, 34) = 19.84$, $p < .001$, $\hat{\eta}^2 = .54$. Responses were slower for unexpected than expected cards, with larger RT differences at the lowest uncertainty loads. Critically, paired t tests revealed that YA participants responded more quickly to expected than unexpected cards even at the highest uncertainty load where card frequencies were closest to equal (26.7% of one card type, 18.3% of the others), $t(35) = 2.77$, $p = .01$ (Figure 4). For OA, there was a significant Load × Expectancy interaction, $F(2, 38) = 25.26$, $p < .001$, $\hat{\eta}^2 = .57$. OA responded more quickly to expected cards at low and medium uncertainty loads ($ps < .001$), but there was no effect

Figure 2

Both Younger Adults (YA) and Older Adults (OA) Showed an Effect of Uncertainty Load on Average RT



Note. While YA showed no difference between the externally cued and internally driven uncertainty conditions, OA showed significant RT slowing in the externally cued condition at medium and high loads. Error bars reflect standard error of the mean. RT = response time.
** $p < .01$. *** $p < .001$.

of card expectancy on RT at the highest uncertainty load, $t(39) = .38$, $p = .70$.

Associations Between Uncertainty Task Performance and Neuropsychological Measures

Regarding associations between uncertainty task performance and neuropsychological testing (in OA only due to data availability), there were significant negative associations between RT slopes in the internally driven condition and DKEFS Letter Fluency, $r(40) = -.34$, $p = .04$; DKEFS Category Fluency, $r(39) = -.37$, $p = .02$; and global cognition (Repeatable Battery for the Assessment of Neuropsychological Status total score), $r(40) = -.36$, $p = .03$ (Table 3; see Supplemental Figure 1 for scatterplots of significant associations). There were no significant associations between RT slopes in the externally cued condition and any of the neuropsychological tests.

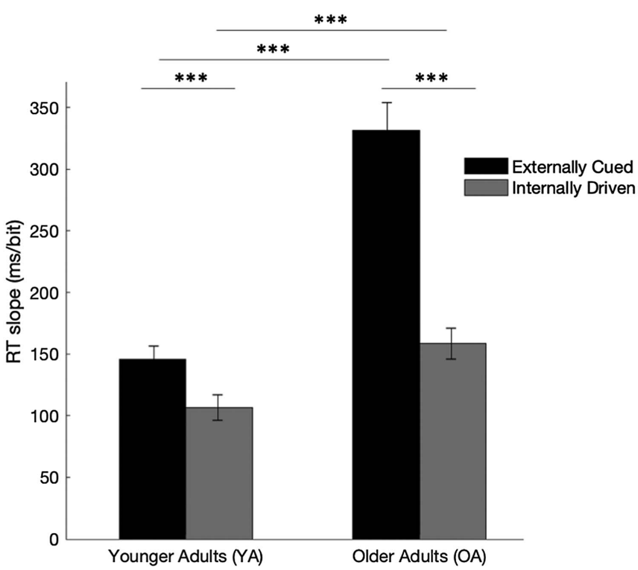
Discussion

We report a distinct pattern of age-related differences in externally cued versus internally driven representations of uncertainty. OA showed greater RT slowing than YA in response to increasing uncertainty loads for both conditions, though the magnitude of slowing was significantly greater for externally cued than internally driven uncertainty. Furthermore, results suggested that OA had impairments in internally driven uncertainty representations at the highest uncertainty load (i.e., when proportions of stimuli were most similar), whereas YA was able to internalize the probability structure of the stimulus deck even when card frequencies were very close to equal (27% of one card type, 18% of the others).

As predicted, RTs in both the externally cued and internally driven uncertainty conditions conformed to the Hick–Hyman law (Hick, 1952; Hyman, 1953), showing a linear increase with increasing uncertainty load. There have been only a couple of studies that investigate the Hick–Hyman law in aging. Our results are consistent with a small ($N = 14$ OA) investigation that showed overall age-related slowing but maintenance of the linear association between uncertainty and RT (Sleimen-Malkoun et al., 2013). We also provide a replication and extension of our previous study, which investigated differential representations of uncertainty in the context of dementia due to AD (Korthauer et al., 2019). In that between-subjects design study, cognitively normal OA showed an approximately threefold increase in slope magnitude in the externally cued compared to internally driven conditions. Here, we demonstrate that both YA and OA show a steeper RT slope (approximately 1.4× higher for YA and 2.2× higher for OA) with increasing externally cued uncertainty compared to internally driven uncertainty. This pattern is consistent with a greater contribution of externally cued uncertainty to choice RT slope under the Hick–Hyman law (Wifall et al., 2016), as the presence of external visual cues helps to coordinate response generation but places greater demands on bottom-up perceptual resources. The greater increase in RT slope for OA compared to YA under externally cued uncertainty is

Figure 3

Younger Adults (YA) and Older Adults (OA) Had Significantly Steeper Slopes for the Externally Cued Than Internally Driven Condition



Note. However, OA had a greater magnitude of difference in slopes, indicating greater age-related difficulty processing externally cued uncertainty. Error bars reflect standard error of the mean. RT = response time.
*** $p < .001$.

consistent with age-related changes in the efficiency of early visual processing, including decreased signal-to-noise ratio (Owsley, 2011) and neural dedifferentiation (Park et al., 2004) in visual cortex.

These findings fit with a broader literature of behavioral and electrophysiological research demonstrating degraded bottom-up perceptual resources in aging, leading to a shift in anteriorly supported top-down processing (Açık et al., 2010; Festa et al., 2017; Lai et al., 2020; Li et al., 2013; Ramzaoui et al., 2021; Zhuravleva et al., 2014). For example, behavioral studies demonstrate that with increasing perceptual load, available attentional resources decrease (Macdonald & Lavie, 2011; Theeuwes et al., 2004), an effect that is magnified among OA (Maylor & Lavie, 1998; Wang et al., 2012). In YA, placing a greater load on perceptual resources is associated with greater engagement of CCN regions, consistent with the interpretation that as perceptual demands increase, these regions exert top-down executive control to bias attentional resources toward task-relevant information (Wei et al., 2013). Thus, age-related disruptions to bottom-up perceptual processing (Açık et al., 2010; Lai et al., 2020; Zhuravleva et al., 2014) may explain why OA show significantly slowed responses as externally cued uncertainty demands increase.

In contrast, the internally driven condition had a fixed number of external cues (i.e., response piles), placing greater demand on top-down executive control processes to develop internal representations of uncertainty at the level of the stimulus. Prior work has demonstrated that the CCN is recruited under these conditions (Wu et al., 2018), and age-related deficits in representing probabilistic information have been associated with differential recruitment of medial prefrontal cortex and anterior cingulate cortex (Samanez-Larkin et al., 2014). These age-related differences are observed under task conditions requiring participants to learn probabilistic stimulus–response information and not when response outcomes are fixed (Samanez-Larkin et al., 2014). In the present study, OA showed steeper RT slopes than YA in the internally driven condition, though the magnitude of this difference was smaller than in the externally cued condition. Furthermore, performance in the internally driven uncertainty condition was associated with global cognitive performance and tests of executive functioning (verbal fluency), consistent with our prior study of patients with AD (Korthauer et al., 2019) and with our interpretation that this condition places greater demand on top-down cognitive control resources.

Perhaps surprisingly, OA showed significantly greater RT in the externally cued than internally driven conditions at the highest uncertainty load where both the overall information uncertainty (2.3 bits) and the number of cards (five) were matched across the conditions. The two conditions were therefore very similar at this uncertainty load, with each having five cards with equal (in the case of externally cued uncertainty) or near-equal (internally driven uncertainty) probabilities. This RT difference highlights the greater processing demands for the externally cued and internally driven conditions. Responding to three cards at the lowest uncertainty level versus five cards at the highest uncertainty level in the externally cued condition requires a different set of cognitive processes, including greater bottom-up perceptual resources, than processing representations of either highly unequal (low uncertainty) versus near-equal (high uncertainty) probability decks of five cards in the internally driven uncertainty condition.

Given these differences, it is more informative to examine the relative change in RT with increasing uncertainty loads (i.e., the

Table 2

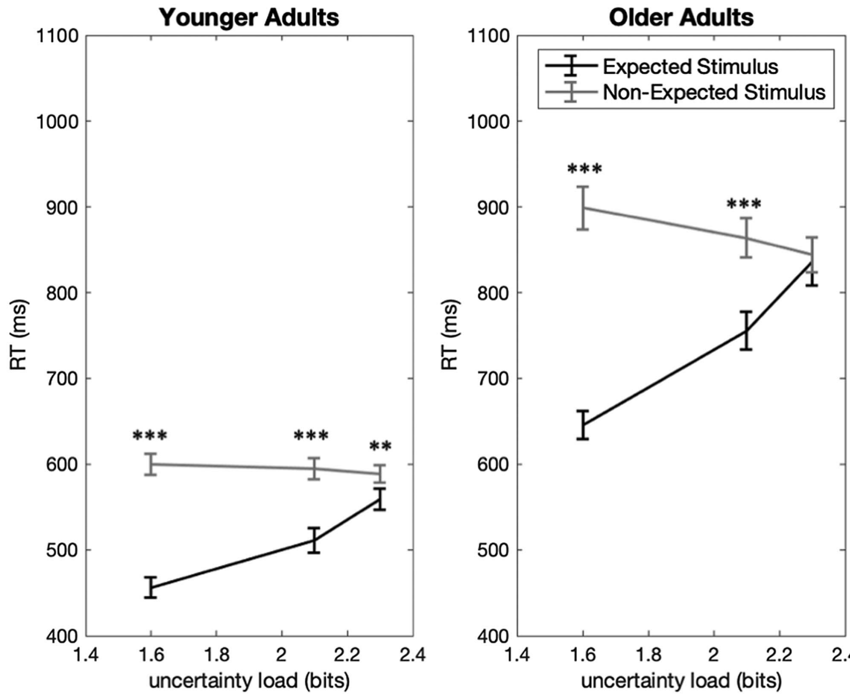
Accuracy for Expected Versus Nonexpected Stimuli in the Internally Driven Condition

	YA			OA		
Uncertainty load	Expected % (*SD*)	Nonexpected % (*SD*)	Wilcoxon test	Expected % (*SD*)	Nonexpected % (*SD*)	Wilcoxon test
Low	98.8 (1.3%)	94.3 (5.0%)	−4.33***	99.5 (0.7%)	97.9 (2.1%)	−3.98***
Medium	97.4 (2.9%)	96.2 (2.9%)	−2.56*	99.0 (1.5%)	97.5 (2.5%)	−3.29**
High	97.4 (3.5%)	96.1 (2.8%)	−2.19*	97.4 (3.5%)	97.6 (1.7%)	−0.257

Note. YA = younger adult; OA = older adult. Nonparametric Wilcoxon signed-rank tests were performed to compare accuracy in response to expected versus nonexpected cards in the internally driven condition. Both YA and OA had higher accuracy for expected than nonexpected cards at low and medium uncertainty loads, while there was no significant difference in accuracy for OA at the highest uncertainty load.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Figure 4

Younger Adults Showed Slower Average RTs for Unexpected Than Expected Cards, With Larger RT Differences at the Lowest Uncertainty Loads



Note. Older adults responded more quickly to expected cards at low and medium uncertainty loads, but not at the highest uncertainty load. Error bars reflect standard error of the mean. RT = response time.
* $p < .05$. ** $p < .01$. *** $p < .001$.

slopes) rather than the absolute RT differences across externally cued and internally driven conditions. While the larger magnitude of slopes in the externally cued condition could be interpreted as being influenced by a practice effect since the externally cued condition occurred before the internally driven condition, there are several reasons why this explanation is unlikely: (a) YA showed no absolute difference in RT between uncertainty conditions at any load, arguing against a practice effect being the primary driver of this effect in OA; (b) the order in which different uncertainty loads appeared was counterbalanced across participants within each uncertainty condition, which would minimize practice effects affecting the overall RT slope; and (c) our previous work using a between-subjects design showed a similar magnitude difference in slopes between the externally cued compared and internally driven uncertainty as in this study (Korthauer et al., 2019). Another possible explanation is that the results could be driven by age-related differences in processing

Table 3

Association Between Uncertainty Task Performance and Neuropsychological Tests

		Correlations with uncertainty condition	
Neuropsychological test	*M* (*SD* [95% CI])	Externally cued slope	Internally driven slope
RBANS total score	106.3 (11.3 [102.8, 109.8])	$r = .14$	$r = -.36^*$
WAIS-IV Digit Span Forward	12.2 (2.3 [11.4, 13.0])	$r = -.13$	$r = -.16$
WAIS-IV Digit Span Backward	9.8 (2.0 [9.1, 10.5])	$r = -.07$	$r = -.04$
Trail-Making Test A	36.1 (9.5 [33.2, 39.0])	$r = .15$	$r = -.04$
Trail-Making Test B	70.4 (25.5 [17.5, 78.4])	$r = .22$	$r = .01$
DKEFS Letter Fluency	47.2 (11.7 [43.6, 50.9])	$r = -.25$	$r = -.34^*$
DKEFS Category Fluency	45.6 (9.5 [42.6, 48.6])	$r = .03$	$r = -.37^*$
DKEFS Category Switching	14.2 (2.7 [13.4, 15.0])	$r = -.30$	$r = -.14$

Note. All results reflect associations in older adults only, due to data availability. Pearson's *r* values are reported. CI = confidence interval; DKEFS = Delis–Kaplan Executive Function System; RBANS = Repeatable Battery for the Assessment of Neuropsychological Status; WAIS-IV = Wechsler Adult Intelligence Scale, Fourth Edition.
* $p < .05$.

speed. However, we view this as unlikely given the absence of an association between a neuropsychological test of psychomotor speed (Trails A) and performance on either condition (Table 3). Instead, we interpret the larger slope for OA in the externally cued condition as representing a different set of cognitive processes, including greater dependence on bottom-up perceptual resources to identify relevant stimuli and possible response alternatives, rather than an order effect or difference in general processing speed.

In addition to the comparison of internally driven and externally cued uncertainty, we further examined stimulus expectancy to provide a more robust test of our hypothesis that age-related changes to the CCN would disrupt internal representations of uncertainty, given the role of the anterior cingulate cortex and anterior insula in mediating stimulus expectancy (Davis & Hasson, 2018; Oliveira et al., 2007; Wu et al., 2021). Although RT based on individual trial expectancy is not directly defined by the Hick–Hyman law, which was outlined at the level of blocks of trials (Hyman, 1953), a recent study extended the law to fit both block- and trial-level data, including surprisal value (Mordkoff, 2017). In the present study, both YA and OA had lower accuracy and greater RTs in response to unexpected (surprising) stimuli, which occurred rarely at the lowest uncertainty load. The critical test of participants' ability to internalize representations of uncertainty was at the highest uncertainty load, when each stimulus had a nearly equal probability of occurring. YA continued to show a difference in accuracy and RT between expected and nonexpected cards despite only subtle differences in the probability structure of the stimulus deck, whereas OA showed no such differences. While this finding is broadly consistent with the brain aging literature that shows subtle age-related disruptions to CCN structure and function (Gold et al., 2010; Grady et al., 2016), future imaging studies examining neural mechanisms underlying age-related differences in internal uncertainty representations are needed.

This study has several limitations. First, all participants completed the externally cued uncertainty task before the internally driven condition. However, the purpose of this design was to provide adequate training for stimulus–response mapping in a condition in which all stimuli occurred equally often. Nonetheless, order effects should be considered when interpreting our results, as uncertainty conditions were not counterbalanced. Additionally, older adult participants were majority White and highly educated, which limits the generalizability of findings. Future studies are needed to investigate these effects in normally aging participants with more representative sociodemographic characteristics. Last, we lacked neuropsychological test data for the YA group and self-reported symptoms of depression or anxiety for all participants. These are important factors that may impact task performance and should be included in future studies.

Taken together, findings demonstrate that the behavior of YA and OA conformed to the Hick–Hyman law, though there were age-related differences in the ability to represent uncertainty and efficiently generate responses. OA had significantly greater difficulty resolving externally cued uncertainty, which places a high demand on bottom-up perceptual resources to coordinate task-relevant action. Furthermore, OA showed a deficit in the ability to generate an internal representation of uncertainty when stimulus probability was near-equal, whereas YA continued to discriminate between more and less frequent stimuli. Collectively, findings provide evidence of age-related disruptions to bottom-up (supported by external visual cues) and top-down (supporting internal mental representations) resources to process uncertainty and coordinate task-relevant action. Future studies investigating the neural mechanisms underlying these age-related differences and using this paradigm in the context of neurodegenerative conditions affecting CCNs may be informative.

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