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Link between fluid/crystallized intelligence and global/local visual abilities across adulthood

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Abstract

Human visual processing involves the extraction of both global and local information from a visual stimulus. Such processing may be related to cognitive abilities, which is likely going to change over time as we age. We aimed to investigate the impact of healthy aging on the association between visual global vs local processing and intelligence. In this context, we collected behavioral data during a visual search task in 103 adults (50 younger/53 older). We extracted three metrics reflecting global advantage (faster global than local processing), and visual interference in detecting either local or global features (based on interfering visual distractors). We found that older, but not younger, adults with higher levels of fluid and crystallized intelligence showed stronger signs of global advantage and interference effects during local processing, respectively. The present findings also provide promising clues regarding how participants consider and process their visual world in healthy aging.

Keywords

Visual processing; Global precedence effect; Fluid intelligence; Crystallized intelligence; Healthy aging

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CRediT authorship contribution statement

Gaelle E. Doucet: Conceptualization, Methodology, Validation, Writing – original draft, Funding acquisition, Supervision. **Noah Hamlin:** Project administration, Investigation, Writing – review & editing. **Jordanna A. Kruse:** Data curation, Writing – review & editing. **Brittany Taylor:** Validation, Formal analysis, Writing – review & editing. **Nicolas Poirel:** Validation, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2022.103429.

1. Introduction

Visual processing largely relies on the identification of the hierarchical levels of visual stimuli, from the most local elements to the largest global level of the stimuli. One solution to investigate these complementary aspects of visual processing has been to use a behavioral task that includes compound stimuli, consisting of large letters (the global level) composed of a suitable arrangement of small letters (the local level) (Navon, 1977). In such paradigms, the participants are instructed to focus on one of the levels (i.e., the “target” level: global or local) and decide on each trial whether a target letter was present in that pre-specified level (e.g., global), while ignoring the other “irrelevant” unattended level (e.g., local). Such visual search tasks led to the reproducible and robust finding that people are faster at detecting information at the global than at the local level (Poirel, Pineau, & Mellet, 2008), which since has been referred to as the global precedence effect (Navon, 1977). Varying stimuli’s characteristics, such as the number of compound stimuli presented at once, allows for further investigation into other types of interference effects such as the impact of number of visual distracting stimuli on local and global processing, which may reflect inhibitory control capacity (Krakowski, Borst, Pineau, Houde, & Poirel, 2015; Poirel et al., 2014).

Recently, we used a three-level hierarchical compound stimuli task to investigate global and local visual processing, and the role of interference effects by visual distracting compound stimuli across adulthood (Bouhassoun, Poirel, Hamlin, & Doucet, 2022; Krakowski et al., 2015; Krakowski et al., 2016). In this task, stimuli were created as a global geometrical form (a circle of a square) composed of several geometrical forms (circles or squares at either an intermediate or local level). Participants were instructed to detect a target geometrical form (i.e., a square) at either level (global, intermediate or local). The target stimulus could be presented either alone or with varying number of hierarchical forms called distractors, composed of circles only. We reported that overall, older adults were slower than the younger adults for visual processing, suggesting lower efficiency to deal with visual distracting stimuli during detail-oriented visual search. Although healthy older adults continued exhibiting a global precedence phenomenon, they were disproportionately less efficient during local aspects of information processing, especially when multiple visual distracting stimuli were displayed, suggesting that they may be less able than younger adults to inhibit visual distracting stimuli to detect local targets (Bouhassoun et al., 2022). In this context, it has been suggested that older participants had disproportional difficulties with inhibiting global interference to efficiently process the local elements (Wiegand et al., 2015). In contrast, other studies have reported changes from global-to-local bias with healthy aging (Agnew, Phillips, & Pilz, 2016; Insch, Bull, Phillips, Allen, & Slessor, 2012; Lux, Marshall, Thimm, & Fink, 2008), with better local processing in older, compared to younger adults. Such discrepancies across studies could be partially related to inter-subject differences in cognitive functions that support visual processing. Indeed, numerous studies have argued that global/local processing could be linked to the efficiency of a wide range of higher-order cognitive processing such as reading, memory abilities or social cognition across the lifespan (Akshoomoff et al., 1993; Gerlach & Starrfelt, 2018; Insch et al., 2012; Oken, Kishiyama, Kaye, & Jones, 1999). Altogether, the question remains whether this altered efficiency in visual processing in late adulthood may be related to declining cognitive capacity typically reported in older age (Ardila, 2007; Ferguson, Brunsdon, & Bradford, 2021).

While it is accepted that visual processing and visual search tasks generally rely on selective attention (Kimchi, 1988) and spatial frequencies processing (Hegde, 2008; Kauffmann, Ramanoel, & Peyrin, 2014), little is known on the specific influence of other major higher-order cognitive functions on either global/local or distractor interference effect. Based upon the seminal work of Navon, it appears that the global precedence effect may be affected by different factors such as complexity, salience or recognizability (Kimchi, 1992; Navon, 1977) and relies on "sensory mechanisms", whereas the global interference effects would rather be associated with identification-related cognitive mechanisms (Poirel et al., 2008). Dore et al. (2018) suggested that visual local–global processing relies more on non-verbal IQ than abstract reasoning, and a study by Zmigrod et al. (2015) concluded that visual processing and the interference effects were correlated with cognitive flexibility, which more strongly relies on fluid intelligence. It is clear that more research is needed to elucidate the link between cognitive functions and visual search processing and how it changes throughout adulthood.

In this context, the current study aimed to identify the link between higher-order cognitive functions and visual search processing using hierarchical compound shape stimuli, in early versus late adulthood. To do so, we recruited 105 healthy volunteers in their early (from 19 to 33 years old) or late (50–81 years old) adulthood. They all completed the same hierarchical visual search task (Krakowski et al., 2015) as well as a cognitive battery (NIH Toolbox) (Weintraub et al., 2014). As measures of cognition, we chose to use reproducible metrics which represent two complementary aspects of higher-order cognition: fluid and crystallized intelligence (Heaton et al., 2014). On the one hand, fluid intelligence (Gf) is defined as reasoning ability, and the ability to generate, transform, and manipulate different types of novel information in real time. Crystallized intelligence (Gc), on the other hand, involves the ability to deduce secondary relational abstractions by applying previously learned primary relational abstractions. These two metrics are differently influenced by aging, with Gf typically showing decline while Gc is typically stable with older age (Akshoomoff et al., 2013; Harada, Natelson Love, & Triebel, 2013). For the visual search task, participants were presented with hierarchical stimuli and were instructed to press a button when a predefined target (i.e., a square) was either present or not at one of the levels of hierarchical stimuli (Fig. 1). Further, the number of visual distracting compound stimuli varied from none to five on the screen while a single target stimulus was simultaneously presented. From this task, we quantified three indices reflecting different aspects of visual processing: a measure of global advantage which refers to the ability to process global information in comparison to the local information, and two measures reflecting the level of interference by visual distracting compound stimuli to local and global processing, respectively, reflecting the ability to resist distractor information during local processing and resist distractor information during global processing. We hypothesized that: (1) the indices reflecting global advantage and interference by the number of distracting compound stimuli to detect local and global targets would be predicted by different performance scores extracted during each local and global search condition between the young and older participants; (2) local and global visual processing would rely on different aspects of higher-order cognition (i.e., fluid vs crystallized intelligence), with this impacted by aging. Particularly, we expected that age-related decline in the level of interference during local processing would be associated with fluid intelligence abilities in older adults. However, because the level of interference during global information processing is overall weak (Poirel et al., 2008) and not impacted by aging (Bouhassoun et al., 2022), we did not expect it to be linked with crystallized or fluid intelligence levels in either group.

2. Material and methods

2.1. Participants

A total of 105 healthy adult individuals were recruited and divided into two age groups: one younger group of 50 participants aged 19–33 years-old and one older group of 55 participants aged 50–81 years-old. This sample size was chosen partially due to our prior research (Bouhassoun et al., 2022) and a power analysis showing that using a linear multiple regression analysis, a minimum sample of 42 participants per age group was needed to detect a modest effect size of $f^2 = 0.2$, with a power of 80 % at $\alpha = 0.05$, therefore we were confident that with our sample of 105 individuals (~50 per group) would achieve significant findings.

All participants were free of psychiatric or neurological disorders and had normal or corrected-to-normal vision (based on self-report). Two participants were excluded from further analyses because of low accuracy during the visual search (<80 %), which resulted in a total of 50 younger adults (mean age ± sd = 25.42 ± 3.40 years, 29 females) and 53 older adults (mean age ± sd = 62.39 ± 6.59 years, 34 females). Groups did not significantly differ in sex ($p > 0.6$), handedness ($p > 0.1$), or education level ($p > 0.4$). However, the older adults had a lower Mini-Mental State Examination (MMSE) score (Younger: mean = 29.30 ± 0.97, range: [26–30]; Older: mean = 28.62 ± 1.43, range: [25–30], $p = 0.006$) and a slightly lower NIH Toolbox crystallized intelligence *t*-score (Younger: mean = 54.33 ± 8.57, range: [39–80]; Older: mean = 50.95 ± 7.39, range: [35–65], $p = 0.013$) (Table 1). The study was approved by the Institutional Review Board for Research with Human Subjects at Boys Town National Research Hospital.

Data from a subgroup of this sample (48.5 %) have been previously published using the same visual search task (Bouhassoun et al., 2022).

2.2. Visual search task

The task used in the current study has been previously validated and published (see Bouhassoun et al. (2022) and Krakowski et al. (2015)). In short, three-level hierarchical stimuli were composed of geometrical forms (circle or square) and included global, intermediate and local levels. Participants were instructed to determine whether a square was present at any level of the hierarchical figure and respond by pressing their index finger for “square present”, and their middle finger for “square absent” as quickly and as accurately as possible. The target (i.e., a square) was present in half of the trials.

In order to increase the task complexity, zero, one, three or five distracting compound stimuli were simultaneously presented on the screen, in addition to the target-present stimulus. These distractors were also three-level hierarchical stimuli, with a circle presented at all levels. In the target-absent trials, circles were presented at all levels for every stimulus (total of 1, 2, 4 or 6 stimuli) on the screen.

The visual search task was presented using a laptop computer with a 11.6-inch screen (refresh rate: 59 Hz) running the E-Prime 3 software application (Psychology Software Tools). The participants viewed the stimuli at a distance of approximately 40 cm. Each of the local elements fits within the confines of virtual square of 0.29° in width and in height. Intermediate geometric figures were 0.86° in width and in height, and global figures were 3.72° in width and in height. Present-target and absent-target compound stimuli appeared equally often in each virtual quadrant of the screen.

Participants started with a training session and were instructed to respond as accurately and as quickly as possible. The training session was repeated until participants were able to correctly perform the task (i.e., ≥ 80 % accuracy). Participants then performed two blocks of 48 trials each, including 24 target-present trials (i.e., 6 trials without any distractors (refer to as the “0D” condition), 6 trials with 1 distractor (“1D” condition), 6 trials with 3 distractors (“3D” condition) and 6 trials with 5 distractors (“5D condition”)) and 24 target-absent trials in each block (i.e., 6 trials per number of hierarchical figures appearing on the screen: 1, 2, 4 or 6 hierarchical figures). The trials were randomized within blocks. In the present-target trials, the target appeared equally often at the global, intermediate, and local levels (for a total of 4 trials per block). Each trial started with the presentation of a blank screen (500 ± 250 ms), then a stimulus was displayed. The stimulus remained on the screen until the participant provided an answer. The stimuli’s positions on the screen were balanced across all conditions. Response times (RTs) and accuracy were recorded. All participants responded with their right hand, using their index finger for target (button 1) and middle finger for non-target (button 2). No participants reported not being able to see the targets at any levels.

2.3. Variables of interest

Based on our hypotheses and previous findings (Bouhassoun et al., 2022; Navon, 1977; Zmigrod et al., 2015), we focused on three measures derived from this task that reflect distinct biases in visual processing (Table 2, Supplementary Table S1). The first index, which we refer to as the global advantage index (GAI), is based on the difference in correct RTs during local versus global identity judgements on target-present trials, in the absence of any distracting stimuli (L0D – G0D; Table 2). Positive values on this index reflect faster processing of global compared with local shape information, in the absence of any distracting stimuli. The second index, which we refer to as the Distractor-Interference Index during Local processing (DII_L), is based on the difference in correct RTs to *local* identity judgements during the 5D condition versus the 0D condition (L5D – L0D; Table 2). In other words, this index reflects the impact of visual distractors on local processing. Accordingly, positive values on this index reflect that increasing the number of visual distracting stimuli interferes more with local shape detection, suggesting greater difficulties to resist to interference (i.e., the capacity for inhibition) during local processing of visual stimuli. The third index, which we refer to as the Distractor-Interference Index during Global processing (DII_G), is based on the difference in correct RTs to *global* identity judgements during the 5D condition versus the 0D condition (G5D – G0D; Table 2). This index reflects the impact of visual distracting stimuli on global processing. Positive values on this index reflect that increasing the number of visual distracting stimuli interferes more with global shape detection, suggesting greater difficulties to resist interference (i.e., the capacity for inhibition) during global processing of visual stimuli. The two conditions in terms of number of distractors (5D vs 0D) and the levels of target detection (local vs global) were specifically chosen because they, respectively, show the strongest interactions between age groups and conditions (Bouhassoun et al., 2022) (Supplementary Fig. S2) and we therefore expected that they should show the strongest difference in these three standard measures of interference biases between the younger and older adults in the current study.

These three indices were computed for each participant as a standardized mean difference (Cohen's d), which is the difference between the two means of interest divided by their pooled standard deviations (Cohen, 1988). As shown previously (Gerlach & Marques, 2014; Gerlach & Poirel, 2018), using such standardized measures yield more reliable estimates than measures based on the absolute differences between means only (which disregard the variance).

The other four considered variables were efficiency scores (Luciana et al., 2018; Vandierendonck, 2017) which reflect the individual performance scores during each of the four visual search conditions of interest (i.e., L0D, L5D, G0D, G5D), respectively. These performance scores are derived from a ratio between the percent accurate and mean RTs for accurate responses. We chose to compute efficiency scores as they provide an integrative score of both RTs and accuracy rates and do not show ceiling effects such as those seen with the accuracy rates for this task (Bouhassoun et al., 2022). They also have been previously validated (Vandierendonck, 2017) and used in other large studies such as the Adolescent Brain Cognition Development (ABCD) project (Luciana et al., 2018; Rosenberg et al., 2020).

Note that the impact of aging on other variables involving other levels (i.e., intermediate), number of distracting compound stimuli (i.e., 1 and 3) and target-absent trials have been presented and discussed in our previous work (Bouhassoun et al., 2022) and will not be further presented in the current study as we found similar patterns (See Supplementary Material).

2.4. Cognitive variables

For each participant, fluid and crystallized intelligence measures were assessed using the NIH Toolbox Cognitive Battery (https://www.healthmeasures.net/explore-measurement-systems/nih-toolbox) (Weintraub et al., 2014). Fluid intelligence is a measure reflecting nonverbal mental efficiency, and capacity in learning and in novel problem-solving, while crystallized intelligence is rather related to verbal capacity and is more dependent upon past learning experiences. Fluid intelligence represents the composite performance score on tasks of memory, executive function, and processing speed; crystallized intelligence represents the composite performance score on tasks on picture vocabulary and oral reading recognition. Fluid and crystallized intelligence scores were therefore considered as complementary measures of cognition as: (1) they are both important in everyday functioning but are differently affected by age (Akshoomoff et al., 2013; Bugg, Zook, DeLosh, Davalos, & Davis, 2006; Harada et al., 2013; Heaton et al., 2014; Horn & Cattell, 1967), and (2) have been shown to be more reliable than the variables extracted from the subtests (Ott et al., 2022; Taylor et al., 2022). The *t*-scores (i.e., corrected for age, sex, ethnicity/race, and education) of each variable were used for further analyses.

2.5. Statistical analyses

Statistical analyses were conducted in three steps. We investigated whether the variability in measures reflecting the GAI (L0D-G0D) or the impact of number of distracting stimuli on global and local processing (DII_L: L5D-L0D and DII_G: G5D-G0D) was driven by:

1. Global and/or local efficiency, and if the effects varied by age group. For this, we conducted separate linear models where each variable of interest (GAI, DII_L and DII_G) was the dependent variable, the age group was a fixed factor and the efficiency variables (L0D and G0D for GAI, L5D and L0D for DII_L, G5D and G0D for DII_G) were entered as continuous covariates. We included the group × efficiency score interactions in each model. False Discovery Rate (FDR) corrections were used to correct for multiple comparisons.

2. Crystallized or fluid intelligence scores. We conducted separate linear models where each variable of interest (GAI, DII_L, DII_G) was the dependent variable, the age group was a fixed factor and the two intelligence variables (Gc and Gf scores) were entered as continuous covariates. We included both group × intelligence score interactions (i.e., group × Gc and group × Gf) in each model. FDR corrections were used to correct for multiple comparisons.

3. Lastly, we conducted mediation analyses to determine the relationship between the intelligence scores, the efficiency scores and the effect sizes. We specifically wanted to assess potential mechanistic pathways through which different aspects of cognition (e.g., verbal and non-verbal) may be associated with performance on the task (e.g., global advantage, distractor interference, etc.). Based on the significant findings from steps 1 and 2, we specifically tested whether the efficiency scores mediated the relationship between the intelligence scores (Gc and Gf, respectively) and the GAI and DII_L indices. Because traditional tests of indirect effects often violate the assumption of normality, we utilized asymmetrical confidence intervals which best represent the true distribution of the indirect effect (i.e., the product of coefficients from the “a” and “b” paths). Thus, we examined the 95 % confidence intervals of bias-corrected bootstrapped confidence intervals based on 1,000 bootstrapped samples (Efron & Tibshirani, 1986), which provide a robust estimate of mediation effects and are asymmetrical (Fritz & Mackinnon, 2007). For each mediation analysis, we employed a multigroup modeling approach (Wang & Wang, 2020) to directly compare the strength and direction of each effect in older versus younger adults. Thus, models for older and younger adults were estimated simultaneously, but separately. Effects were compared between groups within the modeling scheme using model constraints to compute Z tests.

Because of the significant difference in MMSE between the groups, all second level analyses were conducted with and without the MMSE scores as a covariate of no interest. All results remained the same when adding the MMSE variable, therefore we only report the results without.

Given the slight difference in Gc scores between groups, as well as the presence of a few sparse outliers in the sample, group analyses were also reconducted using the raw (uncorrected) Gf and Gc scores, as well as with and without the outliers. Results remained unchanged in all cases.

Linear models were conducted in R v4.0.3, using the *lm* function; and the mediation analyses were conducted in Mplus version 8.1.

3. Results

3.1. Description of the three indices (GAI, DII_L, DII_G)

The distributions of the three indices are displayed in Fig. 2. Across all participants, the mean score on the Global Advantage Index (GAI, L0D – G0D) was 0.98 (SD = 1.22), indicating that participants generally responded faster for the global condition, compared to the local condition, in the absence of any distractor.

Across all participants, the mean score on the Distractor-Interference Index during Local processing (DII_L, L5D – L0D) was 1.71 (SD = 1.13), reflecting that the number of distracting stimuli largely interfered with report of local shape identity. In contrast, across all participants, the mean score on the Distractor-Interference Index during Global processing (DII_G, G5D – G0D) was associated with a small effect size of 0.38 (SD = 0.89), reflecting that the number of distracting stimuli only weakly interfered with report of global shape identity. None of these variables significantly differ between the two groups (all p’s > 0.5).

3.2. Association between indices and efficiency ratios

The Global Advantage Index score was positively associated with G0D efficiency (estimate = 2.36, SE = 0.41, p = $1.E^{-7}$) and negatively with L0D efficiency scores (estimate = −1.61, SE = 0.57, p = 0.005; Fig. 3). There was no significant interaction with age groups. This indicates that, regardless of age, stronger global advantage was driven by both faster detection of global compound stimuli and slower detection of local features.

The other two indices reflecting the interference effect of number of distracting stimuli on local and global detection of visual stimuli (DII_L and DII_G) showed similar patterns: they were positively associated with L0D and G0D efficiency ratios, respectively (L0D: estimate = 1.64, SE = 0.57, p = 0.005; G0D: estimate = 1.78, SE = 0.26, p = $9E^{-10}$) and negatively with the L5D and G5D efficiency ratios, respectively (L5D: estimate = −1.97, SE = 0.62, p = 0.002; G5D: estimate = −1.37, SE = 0.33, p = $7E^{-5}$; Fig. 3). No significant main effect of groups or interactions were revealed for either model (all p > 0.1). These findings indicate that, regardless of age and hierarchical level of the visual target to detect, stronger interference effects by visual distracting stimuli are driven by both faster detection of single stimuli and higher inefficiency of detecting a visual target in presence of several visual distracting compound stimuli.

3.3. Association between indices and cognitive scores

We then investigated whether the global advantage and distractor interference effects were predicted by intelligence scores and varied by age groups. For the Global Advantage Index, we found a significant group × Gc interaction (estimate = 0.09, SE = 0.04, p = 0.011; Fig. 4A). Higher Global Advantage Index was positively associated with Gc in older adults (Spearman r = 0.36, p = 0.009) but not in younger adults (Spearman r = −0.18, p = 0.21). No significant association with Gf was revealed (Table 3).

For the Distractor-Interference Index during Local processing, we found a significant group × Gf interaction (estimate = 0.05, SE = 0.02, p = 0.032; Fig. 4B), though the effect was not significant after FDR correction (p_{FDR} = 0.160). Higher DII_L was positively associated with Gf in older adults (Spearman r = 0.29, p = 0.036) but not in younger adults (Spearman r = −0.12, p = 0.39). Importantly, this interaction remained significant if the DII_L was recomputed based on the average effect size across 1, 3 and 5 distractors versus 0 distractor (p = 0.018). No significant association between Gc and the DII_L was revealed (Table 3).

For the Distractor-Interference Index during Global processing, there was no significant association with either Gf or Gc scores or interactions with group (Table 3). These results remained statistically non-significant if the DII_G was recomputed based on the average effect size across 1, 3 and 5 distractors versus 0 distractor (p > 0.14 for both cognitive measures).

3.4. Mediation analyses

Finally, based on the previous findings, we specifically probed the potential mediating effects of efficiencies on the associations between intelligence scores (Gc and Gf) and the GAI and DII_L indices in a multigroup modeling approach, which allowed us to directly compare effects between older and younger adults (Fig. 5). Again, this was to probe potential mechanisms through which cognitive abilities are associated with local versus global processing abilities in older versus younger adults. Crystallized intelligence was not significantly associated with efficiencies in either age group, though we did see robust associations between both efficiencies and the Global Advantage Index (Fig. 5A). Further, there was a significant direct effect of crystallized intelligence on the Global Advantage Index, but only among older adults (Z = −1.87, *p* = 0.031). Specifically, older adults with greater crystallized intelligence scores tended to have a larger Global Advantage Index (β = 0.24, b = 0.050, *p* = 0.032). We found a significant total indirect effect of crystallized intelligence on the Global Advantage Index among older adults (β = 0.13, b = 0.027, 95 % CI = [0.001, 0.064]), but not among younger adults (β = −0.048, b = −0.007, 95 % CI = [−0.032, 0.017]). That said, the indirect effects did not significantly differ between age groups (Z = −1.41, *p* = 0.079). There were no specific indirect effects that were statistically significant for either group.

With regard to the model of fluid intelligence predicting Distractor-Interference Index during Local processing (DII_L, Fig. 5B), among older adults, fluid intelligence was significantly associated with local zero distractor efficiency (L0D; β = 0.29, b = 0.007 *p* = 0.027) and

DII_L (β = 0.37, b = 0.026 $p = 0.028$), but not with local 5 distractor efficiency (L5D). Additionally, both efficiencies were robustly associated with DII_L (*L0D*: β = 0.55, b = 2.47 $p < 0.001$; *L5D*: β = −0.58, b = −3.40 $p < 0.001$). In contrast, there were no associations between fluid intelligence and any other measures among younger adults; however, both efficiencies were associated with the DII_L (*L0D*: β = 0.37, b = 1.67 $p = 0.004$; *L5D*: β = −0.40, b = −1.98 $p = 0.002$). Further, we found that the effect of fluid intelligence on DII_L was significantly stronger in older adults relative to younger adults (Z = −2.12, $p = 0.017$). Finally, there were no statistically significant indirect effects for either group.

4. Discussion

The current study aimed to determine the influence of fluid and crystallized intelligence on the local and global aspects of visual processing in early versus late adulthood. For this, we used a complex hierarchical visual search task that allowed us to quantify the global precedence effect (i.e., faster global processing than local processing, using the GAI), as well as the interference effect by the number of visual distracting compound stimuli displayed at once, during global and local processing (measured by the DII_G and DII_L, respectively). Overall, we replicated previous studies (Bouhassoun et al., 2022; Navon, 1977; Poirel et al., 2008) by revealing a strong global precedence effect and interference effect for local processing in both younger and older groups. In contrast, the impact of distracting stimuli during global processing was minimal across all participants, which has also been reported in previous studies (Kimchi, Hadad, Behrmann, & Palmer, 2005; Krakowski et al., 2015). We further demonstrated that each index (GAI, DII_L and DII_G) investigated seem to increasingly rely on distinct intelligence abilities -fluid and crystallized-with older age.

The impact of aging on the global precedence and interference effects on visual search has been a matter of debate until now. On the one hand, global processing has been suggested to be affected by age with a decline of global precedence in older participants (Oken et al., 1999; Staudinger, Fink, Mackay, & Lux, 2011). Staudinger et al. (2011) showed, for example, that older adults were less impacted by the variation in the numbers of local elements that form the global level information, than younger adults, suggesting a deficit in global perception. On the other hand, other studies did not report an age effect on the global precedence phenomenon (Bruyer & Scailquin, 2000; Bruyer, Scailquin, & Samson, 2003). Our results seem to support this latter direction as we did not reveal any significant differences for any of the metrics between the two age groups, despite differences in reaction times (see also Supplementary Material).

While previous studies have suggested that populations with either cognitive or visual impairments would show different roles of local and global efficiency in visual processing (Himmelbach, Erb, Klockgether, Moskau, & Karnath, 2009; Mobbs et al., 2007), our participants had relatively high cognitive functioning and corrected-to-normal vision. In our case, this may suggest that both local and global biases play a balanced role to support global precedence effect and other interference effects to visual processing in cognitively healthy populations. Our findings further expand that such mechanisms remain present in late adulthood.

We revealed that metrics related to global advantage and visual distractor interference during local processing (GAI and DII_L) were linked to higher intellectual capacity in older, but not younger, adults. In contrast, the variability in the metric reflecting the level of interference of distractors to detect global features of stimuli (DII_G) seemed to be independent of crystallized and fluid intelligence across both groups. We believe that this lack of association may be related to the actual global advantage effect, as individuals are not affected by distracting stimuli to process global information, which has been consistently reported in previous studies (Krakowski et al., 2015; Navon, 1977; Poirel et al., 2008).

In the current study, we found that older adults with higher crystallized intelligence also had higher global advantage, which indicates that they were faster to detect global than local features. This suggests that older adults with more maintained cognitive abilities may be more sensitive to overall information present in their visual environment, which leads to higher global advantage. We believe that it may reflect some level of cognitive reserve where older adults with higher cognitive capacity must be more focused on all information present in their environment to ensure the detection of relevant information, compared to older adults with lower cognitive abilities. Therefore, older adults with higher cognitive capacities may be more sensitive to interference from irrelevant information and show larger effects of global advantage during visual processing. This possibility is also consistent with previous studies which demonstrated that higher global advantage effect has a positive impact on higher-order cognition such as improving face and object recognition (Forster & Dannenberg, 2010; Gerlach & Starrfelt, 2018).

In agreement, we also found that older adults with higher fluid intelligence were more sensitive to visual distractors when they had to process local visual information, leading to higher DII_L scores. Fluid intelligence typically shows decline with aging and is linked to executive functioning (Bugg et al., 2006; Horn & Cattell, 1967). Consistent with our findings regarding the GAI, we believe that older adults with more intact executive functions (as reflected by higher fluid intelligence) may try to integrate all incoming information (in comparison to older adults with lower executive functions), leading to the necessity to inhibit more non-essential information to correctly focus on a particular target. Even though being able to consider all present visual information is useful in many daily life situations, this may have a negative impact on performance during specific life situations. For instance, while driving, older adults might be less efficient to focus on relevant and essential information in the environment during a heavy traffic situation, which may lead to higher risks of accidents. In this case, the present results suggest that a preservation of fluid intelligence abilities may not be necessarily associated with more secure driving abilities. While it is not possible to validate this hypothesis with the current data, future studies should test it in more real-life situations, such as driving. Alternatively, our findings may be related to the negative impact of aging on response inhibition, where older adults have a lower ability to inhibit an automatic response in favor of producing a novel response, in comparison to younger adults (Harada et al., 2013).

Lastly, it is worth noting that we did not find any significant association between any of the three metrics reflecting visual processing and higher-order cognition in the younger adults. This is likely due to the low level of difficulty of this visual search task. It further implies that the role of cognition on visual processing may progressively strengthen with older age. An alternative explanation is that there was not enough inter-subject variability in the features investigated and cognitive abilities to detect an association between them in the younger group. In order to identify which option is the most accurate, it will be interesting to design a more complex visual search task and test it in young healthy adults.

While this study has many strengths such as a relatively large sample size and reproducible findings, we should acknowledge some limitations. Notably, the metrics we chose to analyze (GAI, DII_L and DII_G) are fully dependent on this hierarchical visual search task. While this task has been used across different populations and showed strong reproducibility in the findings (Hegde, 2008), we cannot totally ensure that the findings would remain the same if the visual search task was more naturalistic, even though precedent studies found a strong link between hierarchical stimuli and natural object processes (Gerlach & Poirel, 2018). The choice of using the conditions with 0 and 5 visual distractors is also arguable. Based on our previous studies (Bouhassoun et al., 2022; Krakowski et al., 2015), these two conditions have been consistently shown to be the easiest and most difficult for participants, respectively, and we therefore focused on them to investigate the link between visual and cognitive abilities. Importantly, it is worth noting that our main results (interaction between age group and cognitive variables) were replicated even after using a combination of all conditions with at least one visual distractor versus the zero-distractor condition, which suggests that our results are robust and independent of the number of distractors presented. However, further studies will be necessary to replicate and investigate natural stimuli situations and scene perception in older adults. Lastly, it is also likely that further differences between subgroups within the older group could be revealed (e.g., between participants aged 50–70 years-old and participants above 70). Indeed, previous aging-related studies that reported a clear bias towards global processing in older adults had an average age of 70 years or younger (Agnew et al., 2016; Bruyer & Scailquin, 2000; Bruyer et al., 2003; Georgiou-Karistianis et al., 2006; Roux & Ceccaldi, 2001) while studies that revealed a bias towards local analysis were based on studies including octogenarian individuals (Oken et al., 1999). Such subgroups could also help identify and improve our understanding of the association between preserved versus declining cognition and visual processing in late adulthood. However, our sample size was too small to statistically test such differences. Nevertheless, the present results provide new information regarding how higher-order cognitive abilities impact visual processing with older age, which is in line with the view that both global advantage and interferences from global and local information rely on cognitive abilities, such as attentional or inhibitory control processes (e.g., Hubner, 2000; Poirel et al., 2014) which affect primary visual areas (e.g., Fink et al., 1996; Fink et al., 1997; Kauffmann et al., 2014), as early as childhood (Poirel et al., 2011).

5. Conclusion

The current study showed for the first time that responses to visual compound stimuli are impacted by variability in cognition in later life. Our study investigated the age-related changes during global/local processing in relation to either fluid or crystallized intelligence and showed a strong relation between high cognitive and high global/local visual abilities in older participants. The present results provide promising clues for future investigations regarding how participants process their visual world throughout the lifespan.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

Data will be made available on request.

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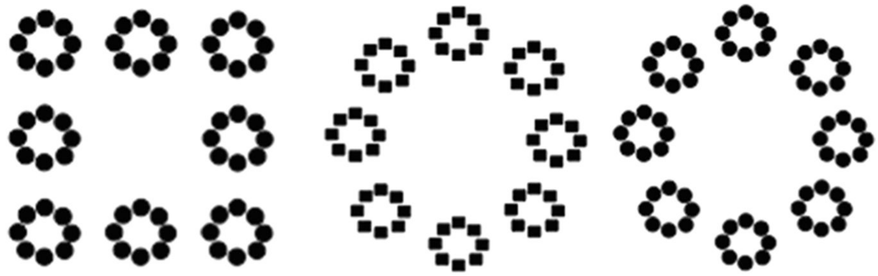

Fig. 1. Stimuli with global and local hierarchical levels

Note. The target is a square at one of the levels. In the task used in the present experiment, a square is the predefined target and could be absent or present at either level.

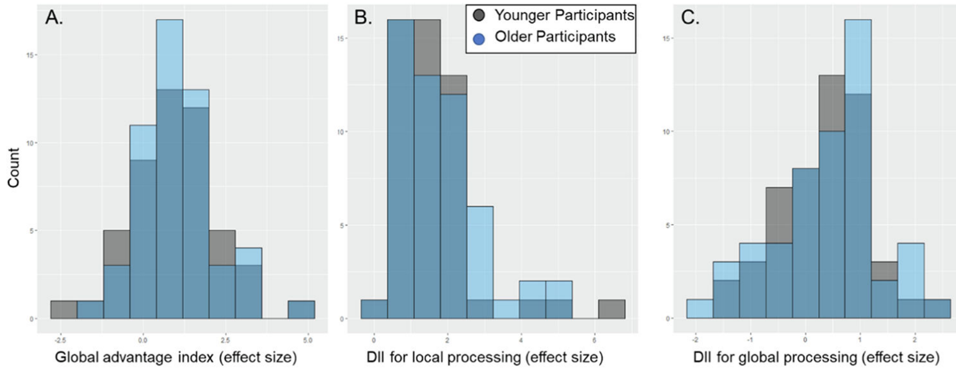

Fig. 2. Distribution of the variables of interest

Note. (A) Global advantage index (L0D-G0D); (B) Distractor-Interference Index for Local processing (L5D-L0D); (C) Interference-to-Distractor Index during Global processing (G5D-G0D).

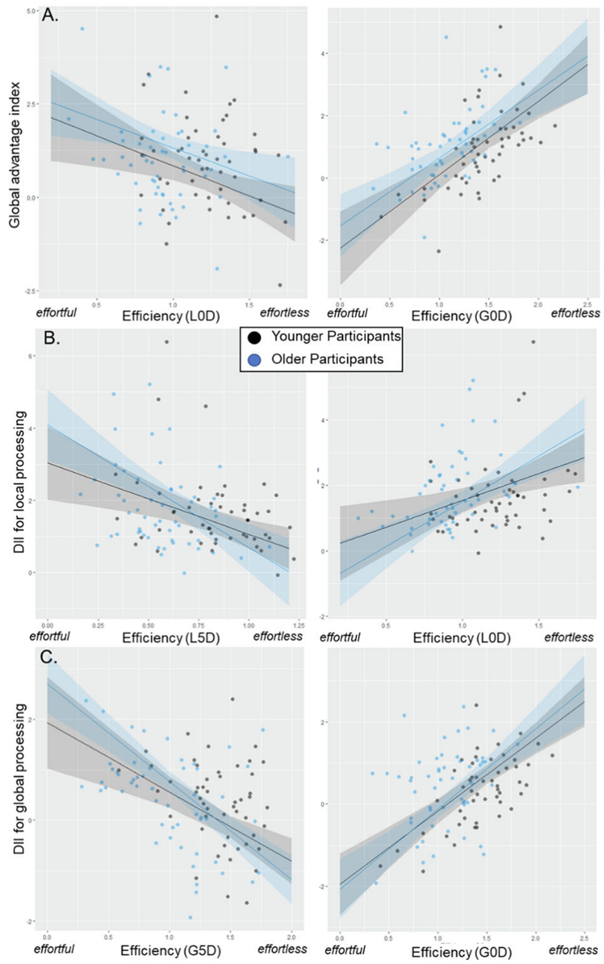

Fig. 3. Association between efficiency ratios and global advantage (A), Distractor-Interference Index for Local processing (B), and Distractor-Interference Index for Global processing (C)

Note. No interactions with the age groups were detected.

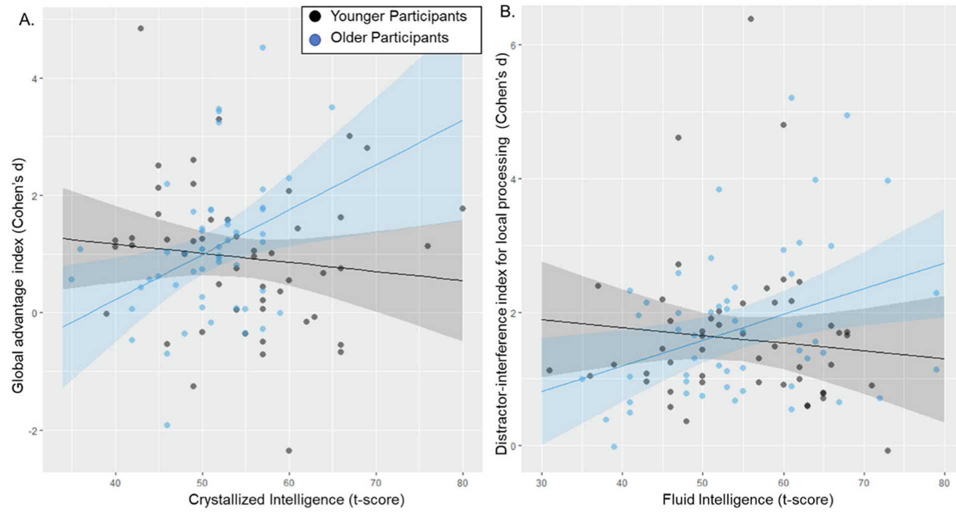

Fig. 4. Association between intelligence scores and global advantage index (A) and Distractor-Interference Index for local processing (B)

Note. Both panels show a significant interaction with age groups, where the older, but not the younger, group demonstrates a significant positive association between the variables of interest.

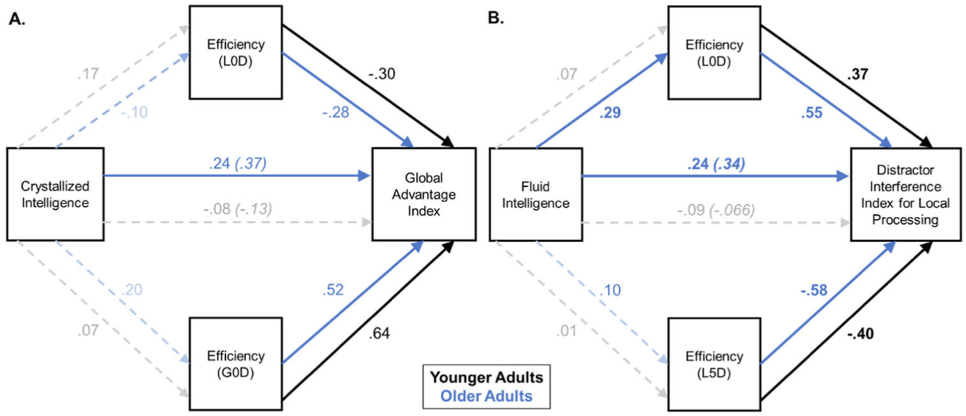

Fig. 5. Results of the mediation analyses

Note. (A) model predicting global advantage index (GAI, L0D-G0D); (B) model predicting Distractor-Interference Index for Local processing (DII_L, L5D-L0D). Straight and darker lines indicate significant relationships. Dashed and Lighter lines indicate non-significant links. For the effects of intelligence scores on GAI and DII_L, values outside of parentheses are direct effects, and values italicized inside parentheses are total effects. All reported effects are standardized.

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Table 1

Demographic Information of each age group.

Variables	Younger Adults (n = 50)	Older Adults (n = 53)	Statistics
Age, years	25.42 (3.40)	62.39 (6.59)	T = −36.1, p < 0.001
Sex, n (%) females	29 (58 %)	34 (64 %)	X^2 = 0.2, p = 0.66
Handedness, n (%) right-handed	47 (94 %)	43 (81 %)	X^2 = 4,0, p = 0.13
education level, years	16.14 (1.19)	16.48 (2.07)	T = −0.8, p = 0.4
MMSE	29.3 (0.97)	28.62 (1.43)	T = 2.8, p = 0.006
Fluid Intelligence (*t*-score)	54.55 (9.86)	54.63 (10.28)	T = 0.01, p = 0.99
Crystallized Intelligence (*t*-score)	54.33 (8.57)	50.96 (7.39)	T = 2.5, p = 0.013

Mean (SD).

Table 2

Description of the variables of interest, extracted from the visual search task. More detail and formula are presented in Supplementary Table S1.

Index type	Variable	Definition
Effect Size	L0D-G0D	Global Advantage Index (GAI) Effect size between the condition Local-0Distractor and Global-0Distractor within each participant. Higher score reflects higher global advantage effect.
Effect Size	L5D-L0D	Distractor-Interference Index for Local processing (DII_L) Effect size between the condition Local-5Distractors and Local-0Distractor within each participant. Higher score reflects higher interference of the number of distractors on the identification of local targets.
Effect Size	G5D-G0D	Distractor-Interference Index for Global processing (DII_G) Effect size between the condition Global-5Distractors and Global-0Distractor within each participant. Higher score reflects higher interference of the number of distractors on the identification of global targets.
Efficiency Score	L0D	Efficiency ratio to detect a local target in the 0-Distractor condition. Higher value reflects higher efficiency to identify the target at the local level, in the absence of any distractors.
Efficiency Score	L5D	Efficiency ratio to detect a local target in the 5-Distractors condition. Higher value reflects higher efficiency to identify the target at the local level, in the presence of 5 distractors.
Efficiency Score	G0D	Efficiency ratio to detect a global target in the 0-Distractor condition. Higher value reflects higher efficiency to identify the target at the global level, in the absence of any distractors.
Efficiency Score	G5D	Efficiency ratio to detect a global target in the 5-Distractors condition. Higher value reflects higher efficiency to identify the target at the global level, in the presence of 5 distractors.

Table 3

Results of the linear models testing the link between the effect sizes and intelligence scores.

Variables	Estimate	Std. Error	t value	P-value (unc)	p_{FDR}
Model for Global Advantage Index (GAI, L0D - G0D)					
Intercept	2.13	1.23	1.74	0.086	
Age Group	−5.03	2.11	−2.39	**0.019**	**0.048**
Crystallized Intelligence	−0.02	0.02	−0.80	0.426	0.710
Fluid Intelligence	−0.01	0.02	−0.31	0.761	0.783
Group × Crystallized Intelligence	0.09	0.04	2.59	**0.011**	**0.048**
Group × Fluid Intelligence	0.01	0.02	0.28	0.783	0.783
Model for Distractor-Interference Index for local processing (DII_L, L5D - L0D)					
Intercept	1.55	1.14	1.35	0.179	
Age Group	−0.78	1.96	−0.40	0.691	0.691
Crystallized Intelligence	0.01	0.02	0.72	0.472	0.620
Fluid Intelligence	−0.01	0.02	−0.68	0.496	0.620
Group × Crystallized Intelligence	−0.03	0.03	−1.04	0.302	0.620
Group × Fluid Intelligence	0.05	0.02	2.17	**0.032**	**0.160**
Model for Distractor-Interference Index for global processing (DII_G, G5D - G0D)					
Intercept	0.79	0.91	0.87	0.389	
Age Group	−0.72	1.57	−0.46	0.647	0.810
Crystallized Intelligence	0.01	0.01	0.61	0.543	0.810
Fluid Intelligence	−0.02	0.01	−1.24	0.220	0.810
Group × Crystallized Intelligence	0.02	0.03	0.61	0.541	0.810
Group × Fluid Intelligence	0.00	0.02	0.02	0.986	0.986

Note. Significant variables at $p_{unc} < 0.05$ are in bold.