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The depth of executive function: Depth information aids executive function under challenging task conditions

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Abstract

The present studies investigated how three core aspects of executive functioning may be influenced by the presence of depth information. Specifically, participants were assigned to one of three executive functioning tasks: working memory (i.e., a change detection task), selective attention (i.e., a visual search task), or inhibitory control (i.e., a flanker task). For all three tasks, participants completed trials where the items in the display were presented either all in one depth plane or the target item was isolated in depth. For the working memory and selective attention tasks, there was an additional condition where items were evenly distributed across two depth planes. Each task also had multiple levels of difficulty to explore if task conditions influence the effect of depth information. Results indicated that although depth information can improve both working memory and selective attention performance, this benefit is specific to the task difficulty and depth information can even hinder performance under certain circumstances. Depth information did not appear to influence inhibitory control performance. Future work is required to investigate if depth can improve inhibitory control performance, and how/what task conditions influence the benefit of depth information. Until further research is completed, researchers and designers should be cautious when implementing multidimensional (3D) displays, as it remains unclear if the performance benefits of including depth information outweigh the present costs.

Keywords Executive function · Working memory · Selective attention · Inhibitory control

Introduction

Vision researchers primarily explore visual cognition within two-dimensional displays devoid of depth information (e.g., Eckstein, 2011; Wolfe, 1994). Since our interactions with the real world incorporate depth information, it is prudent to understand how various cognitive abilities may differ with the inclusion of depth information. Recent visual working memory research suggests that including depth information can improve performance (e.g., Chunharas et al., 2019; Qian et al., 2017; Sarno et al., 2019). These findings are consistent with selective attention research that suggests the mere percept of depth may influence visual performance (Enns & Rensink, 1990), and the presence of a depth-aware attentional spotlight (Atchley et al., 1997). Interestingly, both lines of research exist within the realm of executive function abilities.

Executive function is ubiquitous in our daily lives, incorporating our abilities to hold and manipulate visual information in memory, efficiently deploy attention, and inhibit irrelevant visual stimuli (e.g., Chan et al., 2008; Diamond, 2013; Guiney & Machado, 2013; Raver & Blair, 2016). These abilities represent core constructs of executive functioning: working memory, selective attention, and inhibitory control, respectively (Diamond, 2013). Neuroimaging research has demonstrated that all three of these abilities activate similar brain regions, such as the prefrontal and posterior parietal cortices (Curtis, 2006; Curtis & D'Esposito, 2003; Hannah & Jana, 2019; Kalla et al., 2009; Morishima et al., 2009), suggesting they may represent subcomponents of a unified construct. If these functions all constitute the greater ability of executive function, it is possible that they all rely upon similar strategies to effectively operate. Given that research has indicated the benefit of depth information for selective attention and working memory capacity, it is possible that executive function, as represented by the processes thought to underlie the construct, may broadly take advantage of depth information to perform

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more efficiently. The influence of depth information on executive function is of particular importance in high-risk environments that may utilize three-dimensional (3D) displays such as baggage screening, radiology, and aviation. Specifically, does the inclusion of depth information aid users in these complicated tasks, or does depth represent extraneous information? Thus, further research is necessary to understand if depth information may affect the successful deployment of various executive functioning capabilities. The present studies aimed to investigate whether depth information can aid performance across three core aspects of executive function: working memory, selective attention, and inhibitory control.

Working memory

Recent work has suggested that separating visual information in depth can improve working memory ability. Specifically, individuals may chunk or group items by some sort of depth tag to extend their working memory capacity (Qian et al., 2017; Sarno et al., 2019). However, such findings have been inconsistent, sometimes finding no benefit of depth information (Reeves & Lei, 2014), or only a benefit for closer in-depth items (Qian et al., 2017). Sarno et al. (2019) determined that multidimensional displays could aid working memory performance when working memory load was just beyond an individual's capacity, but this benefit did not persist at higher working memory loads. Research from Chunharas et al. (2019) echo these findings, suggesting that separating items across depth planes can improve working memory performance, particularly in larger memory arrays. These initial findings suggest that a certain level of challenge may be necessary to elicit the benefit of depth information, potentially explaining the disparate findings in the literature; past studies utilized limited set sizes and didn't examine if capacity could influence the utilization of depth information (Qian et al., 2017; Reeves & Lei, 2014; Xu & Nakayama, 2007). This account is consistent with the visual attention domain.

Selective attention

Early research exploring the influence of depth information on attention allocation also demonstrated disparate findings. Downing and Pinker (1985) initially discovered that there were attentional costs when an item did not appear in its cued depth, suggesting the presence of some sort of depth-aware attentional spotlight. Ghirardelli and Folk (1996) presented contradictory findings that suggested any attentional spotlight was blind to depth information. Atchley et al. (1997) attempted to resolve these conflicting findings by investigating the differences in methodology between the two studies. Interestingly, their findings revealed that Downing and Pinker (1985) had utilized distractors in their task, whereas Ghirardelli and Folk (1996) did not. It appeared that depth could influence attention allocation; however, the perceptual load of the task had to be sufficient. More recent work by Finlayson et al. (2013) supports this hypothesis, demonstrating depth benefits only exist when certain task conditions are present. Specifically, they only found a depth benefit when the task was a feature search on the target depth plane, and a conjunction search on the nontarget depth plane. Like the working memory findings, it appears that depth benefits to selective attention may be dependent on task conditions such as difficulty.

Inhibitory control

Although little to no research has explicitly examined the influence of depth information on inhibitory control, research does suggest that individuals utilize depth information to focus on task-relevant information and ignore task-irrelevant information. Specifically, a multiple-object-tracking study conducted by Haladjian et al. (2008) demonstrated that participants can ignore task-irrelevant information if it is presented in a distinct depth plane from the target. These findings also indicated that distractors presented in separate depth planes from the target were pre-attentively separated from the targets and required less effort to inhibit compared to distractors that were presented in the same depth plane as the target. Taken together, these findings suggest that individuals may be more effective at inhibiting distracting information in standard inhibitory control tasks, like the flanker (e.g., Eriksen & Eriksen, 1974), if the distractors and target(s) are presented in distinct depth planes.

The present studies

The present studies investigated if depth information uniformly influences different aspects of executive function. To accomplish this, we utilized three distinct tasks to explore performance for the working memory, selective attention, and inhibitory control components of executive functioning (Diamond, 2013). The first task was a change detection task, which examined the role of depth information in working memory abilities (e.g., Awh et al., 2007; Vogel et al., 2005). The second task was a visual search task, which explored the influence of depth on selective attention (e.g., Wolfe et al., 1989; Wolfe, 1994). The last task was a flanker task, which investigated how depth information may improve inhibitory control (e.g., Eriksen & Eriksen, 1974; West & Alain, 2000). All three tasks examined the influence of depth information across multiple difficulty levels (i.e., working memory load, set size, congruence). The results suggest that depth information can improve performance under challenging task conditions for both working memory and selective attention. However, inhibitory control abilities did not appear to be influenced by the depth information. More challenging inhibitory control conditions may be required to elicit a depth benefit.

General method

Participants

A total of 90 ($M_{\text{age}} = 19.00$ years, 57 female) participants were recruited from the University of Central Florida in exchange for course credit. All participants had normal or corrected-to-normal vision (20/32 or better corrected vision on a Snellen eye chart, stereopsis (Stereo Fly test) and color vision (Ishihara's test for color blindness; 13 plates). This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at the University of Central Florida. Informed consent was obtained from each participant.

A repeated-measures ANOVA power analysis in G*Power 3 (Faul et al., 2007), using a Cohen's *f* of 0.39, power of 0.99, an alpha probability of 0.01, a .5 sphericity correction, and a correlation of 0.5 between the repeated measures was conducted for each task. Based on this analysis, 30 participants for each task (a total of 90) should be more than adequate to find depth effects similar to Sarno et al. (2019).

Stimuli and procedure

All three tasks were programmed and run in SR Research Ltd's Experiment Builder. The entire experiment was presented on a Dell Professional P190S, 19-in. monitor at a resolution of 1,280 × 1,050 pixels, with participants seated approximately 44 cm from the screen. All participants viewed anaglyph images and wore red-blue anaglyph glasses to create the percept of depth. All stimuli were first created in Blender or PowerPoint and then transformed into anaglyph images in Adobe Photoshop. Anaglyph images were generated by duplicating each image, colorizing one in red, and the other in blue, and then slightly separating the image (6 pixels). Two distinct depth planes were created by alternating the direction of separation (i.e., red on left, blue on right; red on right, blue on left). Ultimately, half the stimuli appeared to be closer to the viewer, and half of the stimuli appeared to be farther from the viewer. This method has been previously utilized in both Sarno et al. (2019) and Godwin et al. (2017).

Prior to completing the task, all participants were randomly assigned to one of the three tasks (working memory, selective attention, inhibitory control), provided informed consent, and were prescreened for normal vision. Participants then completed a brief demographic questionnaire (e.g., age, gender, race) and were seated at a computer station for the remainder of the study. For all three tasks, there were four optional breaks between the five blocks (one practice block, four experimental), with a mandatory break between blocks three and four. Participants were given practice trials with feedback to familiarize themselves with the task. With the breaks, the entire experiment took approximately an hour.

Working memory task

Method

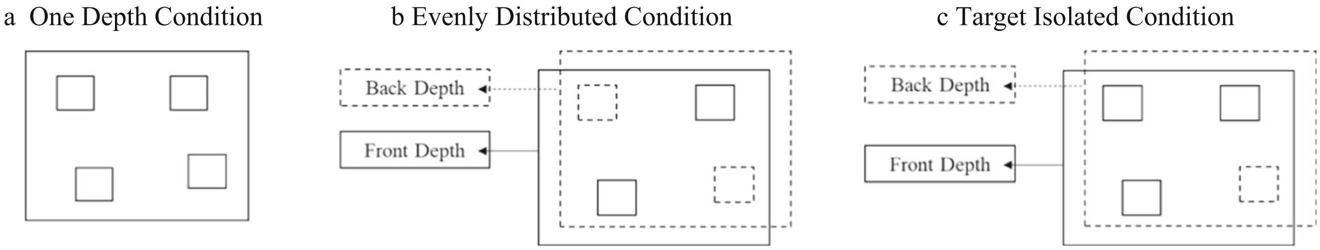
Stimuli and procedure

The influence of depth information on working memory was assessed using a change detection task (e.g., Sarno et al., 2019; Vogel et al., 2005). Stimuli were arrays of 3-D cubes (7.34° × 7.16°) generated in one of seven colors: black, blue, green, violet, red, white, and yellow on a checkered background. The colors were calibrated to avoid any possible distortions from the red/blue filters of the anaglyph glasses. On all trials, participants were tasked to indicate via button press if one of the cubes had changed color. Trials varied based on three variables: set size (2, 4, 6, 8), change presence (change, no change), and depth condition (one depth, target isolated, evenly distributed). Trials were controlled such that each possible trial type (e.g., set size 2, change present, one depth) occurred an equal number of times. Trial order was completely random but remained consistent for each participant. In the one-depth condition, all cubes were presented in one of the two depth planes (i.e., front or back depth) (see Fig. 1a). In the evenly distributed condition, half of the cubes were presented in the front depth plane and the other half were presented in the back depth plane (see Fig. 1b). In the target-isolated depth condition, the probed cube was isolated in depth from the distractors (see Fig. 1c). Each cube was randomly placed within a 3 × 3 grid that excluded the center position. There were a total of 264 trials distributed across one practice block of 24 trials, and four experimental blocks of 60 trials.

Participants were instructed to indicate, via button press, if a circled color cube had changed colors or not. Participants were told that they needed to first focus on a fixation cross (1 s) and that a brief array of cubes would be presented on the screen (500 ms), after which they would have to hold the items in memory (1 s), and then be asked to indicate if the circled item had changed colors.

Results

To investigate the benefit of depth on working memory, classification accuracy was submitted to a 4 (set size: 2, 4, 6, 8) × 3 (depth: one depth, evenly distributed, target isolated) repeated-measures ANOVA. Greenhouse-Geisser corrections were used for analyses where sphericity was violated. There were main effects of depth, $F(2,58) = 3.62$, $p = .033$, partial η^2


a One Depth Condition

b Evenly Distributed Condition

c Target Isolated Condition

Fig. 1 Depth conditions for the working memory task. Dashed lines indicate stimuli in the back depth plane, solid lines indicate items in the front depth plane

= .11, and set size, $F(3,87) = 73.55$, $p < .001$, partial $\eta^2 = .72$, as well as a significant interaction of depth and set size, $F(6,174) = 7.61$, $p < .001$, partial $\eta^2 = .21$ (see Fig. 2). Additional one-way ANOVAs were conducted on each set size to further explore this interaction. There was a main effect of depth for set size 2, $F(2,58) = 15.43$, $p < .001$, partial $\eta^2 = .35$, such that accuracy in the target-isolated condition ($M = .89$, $SD = .09$) and one-depth condition ($M = .91$, $SD = .09$) was higher compared to the even-distribution condition ($M = .84$, $SD = .07$, $ps < .001$). There was no difference between the target-isolated condition and the one-depth condition ($p = .196$). There was a main effect of depth for set size 4 as well, $F(2,58) = 8.21$, $p < .001$, partial $\eta^2 = .22$, such that participants were more accurate in the target isolated in depth ($M = .81$, $SD = .09$) and even-distribution conditions ($M = .77$, $SD = .11$) compared to the one-depth condition ($M = .74$, $SD = .10$; $ps < .024$). There was no difference between the target isolated in depth and even-distribution condition ($p = .100$). Interestingly, this benefit of depth information appears to correlate to the participants' average capacity (K) ($M = 2.93$, $SD = 0.77$). There was no main effect of depth for set size six, $F(2,58) = 1.57$, $p = .217$, partial $\eta^2 = .05$. Lastly there was a main effect of depth for set size 8, $F(2,58) = 7.55$, $p = .001$, partial $\eta^2 = .21$, such that participants were more accurate in the one-depth ($M = .71$, $SD = .13$) and even-distribution ($M = .67$, $SD = .10$) conditions compared to the target isolated in depth condition ($M = .61$, $SD = .13$; $ps < .028$).

Although the overall results demonstrated a benefit of depth at set size 4, some results were surprising – specifically, that there was lower accuracy for the target isolated in depth condition compared to the even-distribution condition at set size 8. Given previous research conducted by Sarno et al. (2019) suggested that differences in working memory capacity may influence the benefit of depth information, additional accuracy analyses were conducted for high- and low-capacity individuals separately. Working memory capacity (K) or the average number of items an individual can remember was calculated utilizing Cowan's methodology (Cowan, 2001). The capacity for each individual was taken as an average across each set size. Participants were then separated into high-capacity ($M = 3.52$, $SD = 0.31$) and low-capacity ($M = 2.33$, $SD = 0.61$) individuals utilizing a median split. To investigate the benefit of depth on working memory, each capacity group was submitted to a 4 (set size: 2, 4, 6, 8) × 3 (depth: one depth, evenly distributed, target isolated) repeated-measures ANOVA.

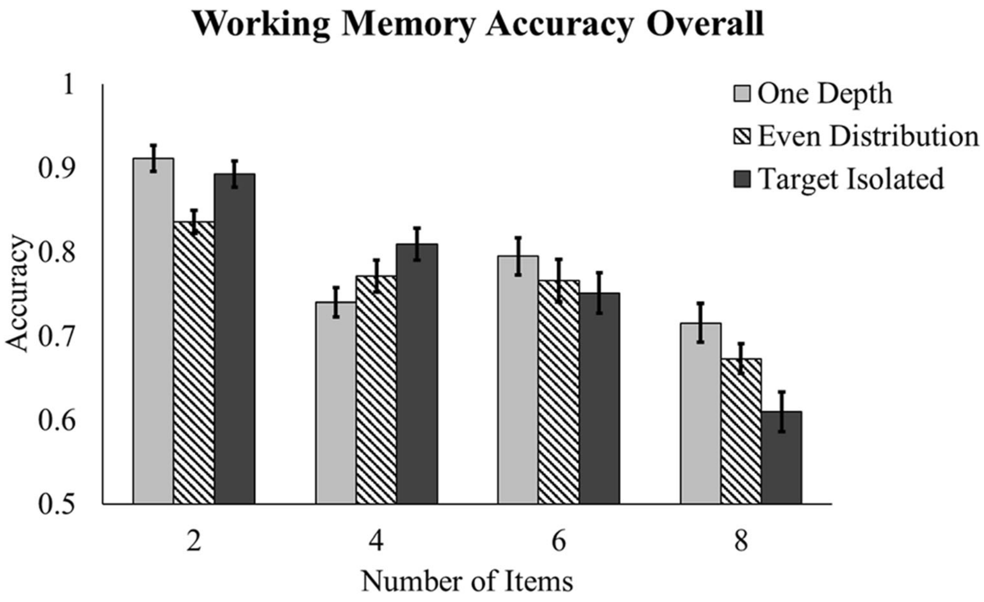


Fig. 2 Accuracy results for the working memory task – all participants. Error bars represent the standard error of the mean

Low-capacity individuals

For the low-capacity individuals, there was no main effect of depth on accuracy, $F(2,28) = 1.16$, $p = .327$, partial $\eta^2 = .08$. There was a main effect of set size on accuracy, $F(3,42) = 43.08$, $p < .001$, partial $\eta^2 = .76$, with accuracy decreasing as the number of items in the display increased. Importantly, there was a significant interaction between depth and set size, $F(6,84) = 3.74$, $p = .002$, partial $\eta^2 = .21$, suggesting that the influence of depth on working memory performance depends on the number of items in the display. Additional one-way ANOVAs on each set size were conducted to further explore this interaction (see Table 1 for full descriptive statistics).

There was a main effect of depth for displays with two items, $F(2,28) = 5.35$, $p = .011$, partial $\eta^2 = .28$, with higher working memory performance in the one-depth plane and the target-isolated depth conditions compared to the even-distributed conditions ($p = .026$, $p = .003$, respectively) (see Fig. 3a). There were no differences between the one-depth and target-isolated conditions ($p = .958$). There were no main effects of depth for the low-capacity individuals for displays with four, $F(2,28) = 2.90$, $p = .072$, partial $\eta^2 = .17$, or six items, $F(2,28) = 0.31$, $p = .74$, partial $\eta^2 = .02$. Lastly, there was a significant main effect of depth for low-capacity individuals in displays with eight items, $F(2,28) = 5.37$, $p = .011$, partial $\eta^2 = .28$. Interestingly, the participants had better performance in the one-depth-plane condition compared to the target-isolated condition ($p = .016$), but not the even-distributed condition ($p = .645$). The even-distributed condition also demonstrated higher accuracy compared to the target-isolated condition ($p = .017$).

High-capacity individuals

Similar to the low-capacity results, there was not a main effect of depth on accuracy, $F(2,28) = 3.32$, $p = .051$, partial $\eta^2 = .19$ (see Fig. 3b). There was a significant main effect of set size, $F(3,42) = 36.19$, $p < .001$, partial $\eta^2 = .72$, with working memory performance decreasing as set size increased. Again, there was a significant interaction between depth and set size, $F(6,84) = 6.56$, $p < .001$, partial $\eta^2 = .32$. Further one-way ANOVAs were conducted for each set size to break down this interaction (see Table 1 for full descriptive statistics).

Like the low-capacity individuals, the high-capacity results demonstrated a main effect of depth for displays with two items, $F(2,28) = 11.33$, $p < .001$, partial $\eta^2 = .45$, with higher

Table 1 Descriptive statistics for each capacity group, depth condition, and set size

Depth condition	Set size	Capacity	Mean	SD
One depth	2	Low	.87	.10
		High	.95	.05
	4	Low	.69	.12
		High	.79	.05
	6	Low	.73	.14
		High	.86	.08
	8	Low	.66	.15
		High	.76	.08
Even distribution	2	Low	.82	.08
		High	.86	.07
	4	Low	.71	.09
		High	.83	.08
	6	Low	.70	.14
		High	.83	.10
	8	Low	.64	.10
		High	.70	.08
Target isolated	2	Low	.87	.11
		High	.91	.05
	4	Low	.76	.08
		High	.86	.08
	6	Low	.69	.12
		High	.81	.09
	8	Low	.53	.10
		High	.69	.09

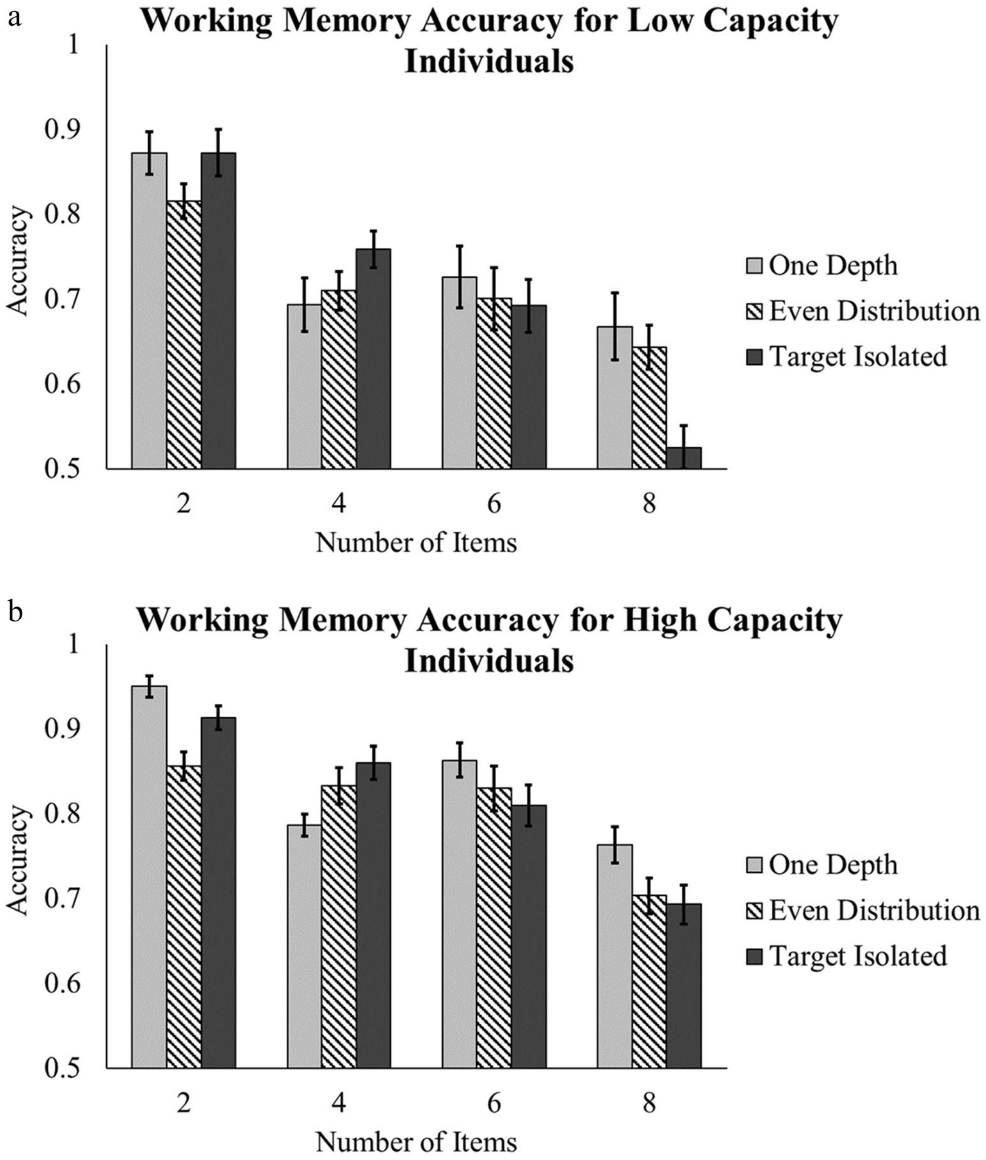


Fig. 3 Accuracy results for the working memory task for high-capacity (**a**) and low-capacity individuals (**b**). Error bars represent the standard error of the mean

accuracy in the one-depth and target-isolated depth conditions compared to the evenly distributed condition (*p*s <.001), but no differences between the one-depth and the target-isolated condition (*p* =.077). Unlike the low-capacity individuals, there was a main effect of depth for displays with four items for the high-capacity individuals, *F*(2,28) = 6.78, *p* = .004, partial η^2 = .33. Specifically, working memory performance was higher in the target-isolated condition compared to the one-depth condition (*p* = .002). Additionally, the evenly distributed condition also demonstrated higher working memory performance compared to the one-depth condition (*p* = .034). The benefit of the even-distribution condition appears to be related to the high-capacity participants' average capacity (*M* = 3.52, *SD* = 0.31). There were no differences between the evenly distributed condition and the target-isolated condition, (*p* = .240). There was no main effect of depth for displays with six items, *F*(2,28) = 2.74, *p* = .102, partial η^2 = .15. Finally, there was a main effect of depth for the displays with eight items, *F*(2,28) = 3.88, *p* = .033, partial η^2 = .22. Similar to what was observed with the low-capacity individuals, the one-depth condition showed higher working memory performance compared to the target-isolated (*p* = .048) and the even-distributed conditions (*p* = .006).

Overall, the results indicated that depth information hindered all participants performance at two and eight items, and only improved performance for high-capacity individuals at four items. It is important to note that the original power analysis indicated a total sample of 30 participants, and separating the high- and the low-capacity individuals broke the sample into two groups of 15 participants. Although we were able to find several significant results, it is possible that some of the null results were slightly underpowered.

Selective attention

Method

Stimuli and procedure

The influence of depth information on selective attention was assessed by a visual search task (e.g., Wolfe et al., 1989). Stimuli were arrays of dark gray Ts and Ls (2.35° × 2.35°) on a light gray background. Bevels were added to the Ts and Ls to provide an additional percept of depth. Participants were asked to indicate if a target (T) was present amongst distractors (Ls). Trials varied based on three variables: set size (8, 16, 32), target presence (present, absent), and depth condition (one depth, target isolated, evenly distributed). Trials were controlled such that each possible trial type (e.g., set size 8, target present, one depth) occurred an equal number of times. Trial order was completely random but remained consistent for each participant. In the one-depth condition, all search items were presented in one of the two depth planes (i.e., the front of back depth) (see Fig. 4a). In the evenly distributed condition, half of the search items were presented in the front depth plane, and the other half was presented in the back depth plane (see Fig. 4b). In the target-isolated depth condition, the target (T) was isolated in depth from the distractions (Ls) (see Fig. 4c). Search items were randomly placed within a 6 × 6 grid. There were a total of 378 trials that were distributed across one practice block of 18 trials, and four experimental blocks of 90 trials.

Stimuli and procedure

Participants were instructed to indicate, via button press, if a T was present in the search array. Participants were told that they needed to first focus on a fixation cross (1 s) and then the search array would appear.

Results

To investigate the benefit of depth on selective attention, both accuracy and response times were submitted to a 3 (set size: 8, 16, 32) × 3 (depth: one depth, evenly distributed, target isolated) repeated-measures ANOVA for target-present trials. Response times were calculated on correct trials.

Accuracy

There was a main effect of set size, $F(2,28) = 16.05$, $p < .001$, partial $\eta^2 = .36$. Pairwise comparisons revealed that participants were less accurate on trials where there were more items (see Fig. 5). There was a main effect of depth, $F(2,28) = 11.87$, $p < .001$, partial $\eta^2 = .29$, and a significant interaction between depth and set size, $F(3.01,87.18) = 7.09$, $p < .001$, partial $\eta^2 = .20$.

To break down this interaction, separate one-way ANOVAs were calculated on each set size to investigate the influence of depth on selective attention (see Table 2 for the full descriptive statistics). There was a main effect of depth for eight items, $F(2,58) = 4.59$, $p = .014$, partial $\eta^2 = .14$. Pairwise comparisons indicated that participants were less accurate in the evenly distributed condition compared to the target-isolated ($p = .010$) and one-depth-plane conditions ($p = .050$). There was no difference between the target-isolated condition and the one-depth condition ($p = .262$). There was no effect of depth when there were 16 items, $F(2,58) = 2.19$, $p = .121$, partial $\eta^2 = .07$. However, there was an effect of depth for trials where there were 32 items, $F(2,58) = 12.74$, $p < .001$, partial $\eta^2 = .31$. Pairwise comparisons revealed that participants were most accurate when the target was isolated compared to the even-distribution ($p = .015$) and one-depth condition ($p < .001$). Participants were also more accurate in the even-distribution condition compared to the one-depth condition ($p = .005$).

To further explore how the depth conditions influenced accuracy, we calculated the accuracy slopes for each condition. Slopes were defined by the change in accuracy for each item added to the array and calculated by measuring the slope of the line between accuracy for 32 items and eight items.

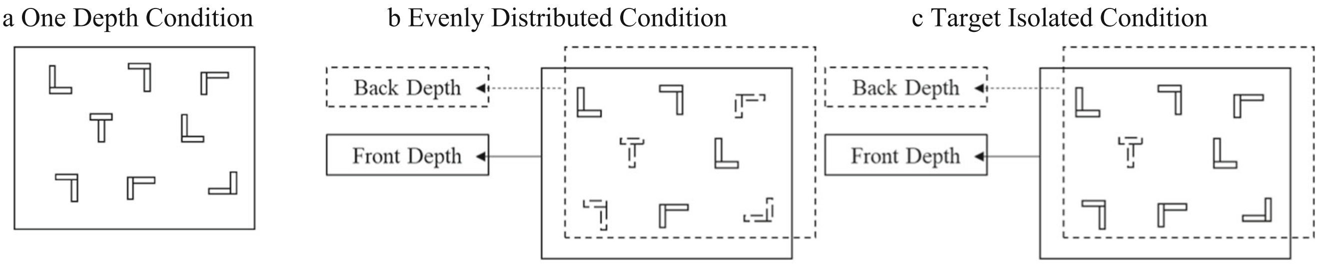


Fig. 4 Depth conditions for the selective attention task. Dashed lines indicate stimuli in the back depth plane, solid lines indicate items in the front depth plane

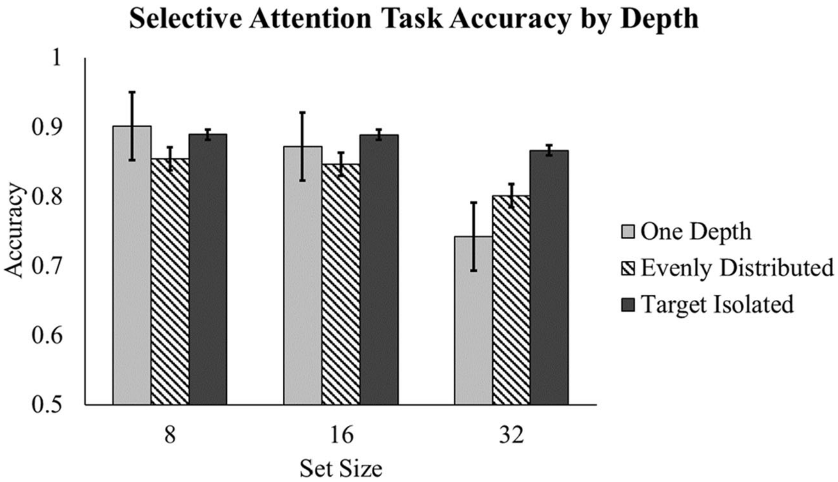


Fig. 5 Accuracy for the selective attention task. Error bars represent the standard error of the mean

Smaller slopes indicate a larger decrease in accuracy for each additional item (Wolfe, 1998). The one-depth-plane condition demonstrated the largest cost for each item (-0.66%/item), followed by the even-distributed condition (-.22%/item), and the target-isolated condition (-0.09%/item). Together, these findings suggest that the availability of depth information insulated participants against accuracy decrements compared to when depth information was not available (i.e., the one-depth-plane condition).

Response times

There was a main effect of set size, $F(1.10,31.88) = 150.98$, $p < .001$, partial $\eta^2 = .84$ (see Fig. 6). Pairwise comparisons revealed that participants were fastest on trials that had fewer items. There was a main effect of depth, $F(1.63,47.21) = 20.67$, $p < .001$, partial $\eta^2 = .42$, and there was a significant interaction between depth and set size, $F(2.57,74.58) = 10.50$, $p < .001$, partial $\eta^2 = .27$.

To break this interaction down further, separate one-way ANOVAs were conducted on each set size to investigate the influence of depth on selective attention (see Table 3 for the full descriptive statistics). There was a main effect of depth for arrays with eight items, $F(1.30,37.72) = 6.78$, $p = .008$, partial $\eta^2 = .19$. Pairwise comparisons revealed that participants were faster in the target-isolated and one-depth condition, compared to the even-distributed condition (*p*s = .009, .012, respectively). There was no difference between the target-isolated condition and the one-depth condition ($p = .720$). There was no main effect of depth for 16 items, $F(1.63,47.29) = 3.66$, $p = .042$, partial $\eta^2 = .11$. However, there was a main effect of depth for arrays with 32 items, $F(1.86,54.02) = 17.46$, $p < .001$, partial $\eta^2 = .38$. Pairwise comparisons indicated that participants were again faster on target-isolated and one-depth trials compared to even-distributed trials (*p*s <.001). However, there was no difference between target-isolated and one-depth trials ($p = .158$).

To further investigate the data, we also examined the search slopes for reaction time. Slopes were defined by the change in response time for each item and calculated by measuring the slope of the line between response times for 32 items and eight items. Larger slopes indicate a larger response time increase for each additional item (Wolfe, 1998). The even-distributed condition demonstrated the largest slope (80 ms/item), followed by the one-depth-plane condition (72 ms/ item) and the target-isolated condition (46 ms/item). In conjunction with the above results, these slopes suggest that the even distribution trials demonstrated the largest response time cost for additional items.

Overall, the selective attention results suggest that depth information can hinder both accuracy and response times on easy trials (i.e., set size 8), and improve accuracy and response times for more challenging trials (i.e., set size 32) when the target is isolated in depth. Participants were also more accurate when items were evenly distributed across depth but were slower to respond.

Inhibitory control

Method

Stimuli and procedure

The stimuli and procedure were similar to the Working Memory and Selective Attention tasks with the following exceptions. The influence of depth information on inhibitory control was assessed by a flanker task (e.g., Eriksen &

Table 2 Descriptive statistics for each depth condition, set size, and target presence accuracy

Depth condition	Set size	Target presence	Mean	SD
One depth	8	Present	.88	.16
		Absent	.97	.07
	16	Present	.89	.16
		Absent	.96	.13
	32	Present	.87	.16
		Absent	.94	.15
Even distribution	8	Present	.85	.18
		Absent	.96	.08
	16	Present	.85	.17
		Absent	.95	.14
	32	Present	.80	.15
		Absent	.96	.09
Target isolated	8	Present	.90	.14
		Absent	.96	.11
	16	Present	.87	.14
		Absent	.97	.09
	32	Present	.73	.22
		Absent	.96	.10

Eriksen, 1974). Stimuli were dark gray arrows (4.41° × 2.35°) on a light gray background. On all trials, participants were tasked to indicate via button press which direction a central arrow was facing (i.e., right vs. left). Trials varied based on two variables: direction congruence with the central arrow (congruent, incongruent), and depth condition (one depth, target isolated). Trials were controlled such that each possible trial type (e.g., congruent and one depth) occurred an equal number of times. Trial order was completely random but remained consistent for each participant. In the one-depth condition, all arrows were presented in one of the two depth planes (i.e., front or back depth) (see Fig. 7a). In the target-isolated depth condition, the central arrow was isolated in depth from the distractor arrows (see Fig. 7b). There were a total of 100 trials that were distributed across one practice block of 20 trials, and four experimental blocks of 20 trials.

Participants were instructed to indicate, via button press, if a central arrow was facing right or left. Participants were told that they needed to first focus on a fixation cross (1 s) and then the flanker array would appear.

Results

To investigate the benefit of depth on inhibitory control, response times were submitted to a 2 (congruence: incongruent,

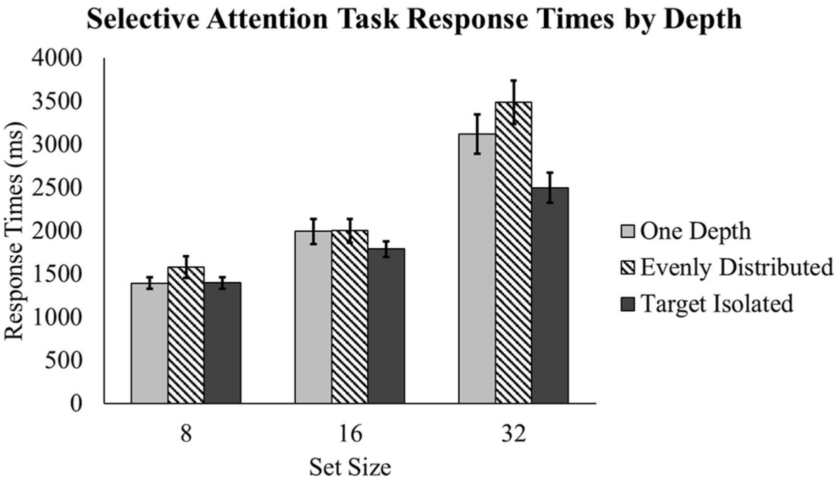


Fig. 6 Response times for the selective attention task. Error bars represent the standard error of the mean

Table 3 Descriptive statistics for each depth condition, set size, and target presence response times (ms)

Depth condition	Set size	Target presence	Mean	SD
One depth	8	Present	1452.61	391.46
		Absent	2509.21	654.89
	16	Present	1881.16	394.48
		Absent	4079.11	1407.26
	32	Present	2740.43	927.31
		Absent	6628.56	2630.03
Even distribution	8	Present	1675.52	632.77
		Absent	2393.82	636.64
	16	Present	2114.07	576.10
		Absent	4084.01	1256.38
	32	Present	3909.49	1259.38
		Absent	6601.97	2734.98
Target isolated	8	Present	1438.66	279.03
		Absent	2450.02	720.17
	16	Present	2060.65	562.11
		Absent	4631.30	3463.40
	32	Present	3639.05	1055.55
		Absent	6372.78	2518.76

congruent) × 2 (depth: one depth, target isolated) repeated-measures ANOVA. Accuracy results were near ceiling performance and are not reported here (one-depth condition: M = .99, SD = .02; target-isolated condition: M = .98, SD = .02).

There were no main effects of congruence, $F(1,29) = 3.37$, $p = .077$, partial $\eta^2 = .10$, or depth, $F(1,29) = 2.08$, $p = .160$, $\eta^2 = .07$. However, there was a significant interaction between congruence and depth, $F(1,29) = 9.08$, $p = .005$, $\eta^2 = .24$ (see Fig. 8). To break this interaction down further, separate one-way ANOVAs were conducted on congruent and incongruent trials (see Table 4 for the full descriptive statistics). For congruent trials, there was a main effect of depth, $F(1,29) = 5.46$, $p = .027$, $\eta^2 = .16$, with participants faster in the one-depth condition compared to the target-isolated condition. For incongruent trials, there was no effect of depth, $F(1,29) = 2.53$, $p = .122$, $\eta^2 = .08$.

We were also interested to examine if a standard flanker effect (i.e., incongruent trials slower than congruent ones) was present in both depth conditions. To examine this, we ran additional separate one-way ANOVAs on the target-isolated and one-depth-plane trials. For the one-depth-plane condition, analogous to most flanker tasks, we did find an effect of congruence, $F(1,29) = 23.51$, $p < .001$, $\eta^2 = .45$, where participants are faster on congruent trials compared to incongruent trials. However, for the target-isolated depth condition, we did not find an effect of congruence, $F(1,29) = 0.04$, $p = .843$, $\eta^2 < .01$. This lack of effect appears to be driven by participants performing worse on the congruent trials when the target is isolated in depth.

Overall, the flanker task findings suggest that depth does not influence inhibitory control, but depth information may cause participants to perform worse on the easy, congruent trials.

General discussion

The present studies investigated the influence of depth information on three core aspects of executive function: working memory, selective attention, and inhibitory control. The findings suggest that depth affects both working memory and selective attention abilities but may not influence inhibitory control. The influence of depth on executive functioning abilities appears to be linked to the difficulty of the task, where easy task conditions may elicit a hinderance of task performance due to the inclusion of depth, and more challenging tasks conditions promote depth-related benefits to performance. However, this benefit appears to be limited for working memory and may only exist just beyond a participants' capacity.

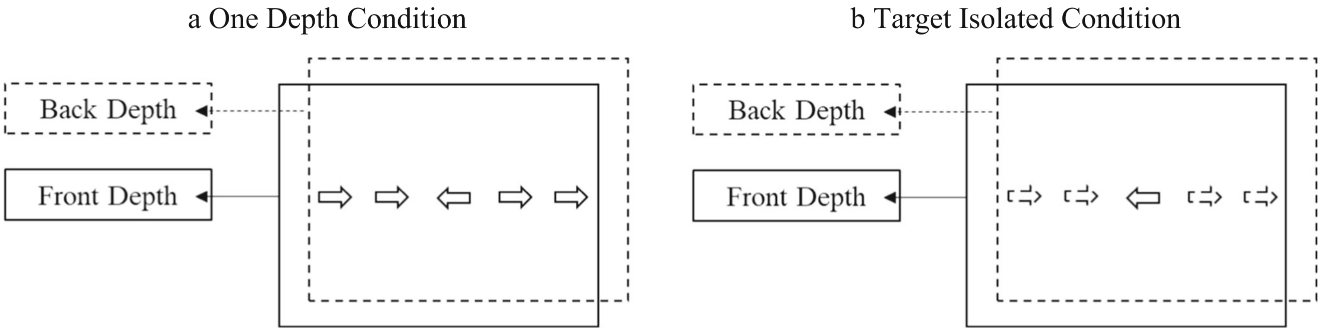


Fig. 7 Depth conditions for the inhibitory control task. Dashed lines indicate stimuli in the back depth plane, solid lines indicate items in the front depth plane.

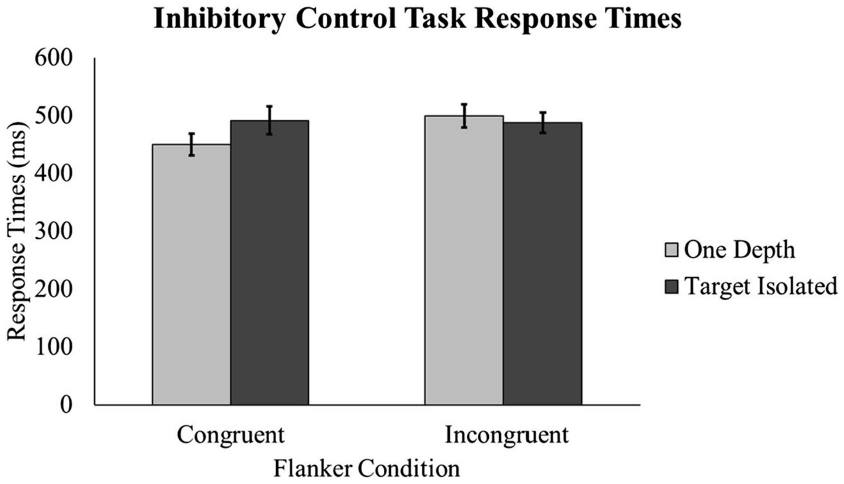


Fig. 8 Response times for the inhibitory control task. Error bars represent the standard error of the mean

Working memory task

Sarno et al. (2019) demonstrated that depth benefits may be linked to working memory capacity and the difficulty of the trial. Specifically, benefits of depth information were only seen on trials that were around an individual's working memory capacity. Similar to Sarno et al. (2019), the present findings demonstrate that the benefits of depth information appear to be dependent on participants' working memory capacity. High-capacity individuals were able to utilize the depth information to improve their working memory performance on trials with four items (just above their capacity – 3.52 items). This benefit was present on trials where the target item was isolated in depth, and where all the items were evenly distributed across depth, relative to the one-depth condition. Although the benefit of depth information existed for displays with four items, participants did demonstrate a hinderance of depth information at the most challenging working memory load (i.e., eight items). Taken together, these finding suggest that the benefit of depth for working memory may be limited to specific task conditions and only available to individuals with higher working memory capacity.

Table 4 Descriptive statistics for each depth condition, and congruence response times (ms)

Depth condition	Congruence	Mean	SD
One depth	Congruent	449.79	202.12
	Incongruent	499.43	108.14
Target isolated	Congruent	491.48	132.87
	Incongruent	487.67	96.99

Selective attention task

The visual search task results provided evidence that suggests task difficulty also influences selective attention. Participants were more accurate at identifying the target on trials that included multiple depth planes, when the items were evenly distributed across depths, and when the target was isolated, for the more challenging set size (32 items). These accuracy improvements were accompanied by an increase in response times for the even-distributed condition. This suggests that although participants can more effectively search for the target when items are distributed across depths, it may come at the cost of speed. Interestingly, participants in the visual search task also demonstrated a depth hinderance on easier trials (eight items). Participants were both less accurate and slower in the even-distribution condition when the display only had eight items. Again, these findings suggest that depth information can aid the accuracy of selective attention, but that this benefit is dependent upon the complexity of the display, and may result in increased time on task.

Inhibitory control task

The inhibitory control task presented a different narrative compared to the other two executive function tasks. Unlike working memory and selective attention, inhibitory control abilities do not appear to benefit from the presence of depth information. However, even though participants demonstrated a standard flanker effect for the one-depth condition, no flanker effect emerged in the depth condition. This pattern of results suggests that depth may be influencing inhibitory control performance, but the task was not challenging enough to find a depth benefit. It is important to note that the lack of a flanker effect in the depth condition appears to be driven by the congruent trials. Specifically, participants were slower on the congruent trials when the central arrow was isolated in depth. Speculatively, this may be because the task was too easy, and the extra depth information makes the task more visually complex without providing a useful strategy to organize the information. Further research is required to explore this hypothesis, perhaps with both more challenging flanker conditions and other inhibitory control tasks.

Task difficulty and the influence of depth

It is possible that the mechanism underlying the benefit of depth information is specific to the component of executive functioning. However, it is also possible that task difficulty broadly influences the utilization of depth information across different aspects of executive function. For example, depth appears to assist working memory ability for individuals who have higher capacity when the task is just outside of their average ability. Vogel et al. (2005) demonstrated that high-capacity individuals are better at excluding irrelevant task information and focusing on the visual information in displays that will aid them in their task. Vogel et al.'s (2005) findings may support the present results, that depth only aids individuals who have higher working memory capacity because they are able to use it as an effective strategy to either encode or retrieve visual information. However, this hypothesis does not explain why task difficulty determines if depth hinders or improves performance, or why depth benefits aren't persistent for displays with six and eight items. It is possible that the strategy utilized is what determines when depth is useful or harmful. Pomplun et al. (2013) observed evidence for different search behaviors based on task difficulty. When examining search behaviors for easy tasks, participants typically employ a more global examination of items in the display, whereas more challenging tasks require viewers to systematically examine each item (often in their reading direction). It is possible that our participants switch strategies, examining the displays depending on the difficulty of the task. On easier trials, with fewer items, participants may deploy attention more broadly and encode information in parallel. However, on more challenging trials, participants may systemically explore the display and serially encode/view each item. If this hypothesis is correct, then it may suggest that individuals only benefit from depth information when it is searched for or encoded serially. This is supported by the visual search findings; participants were slower in the even-distribution condition, potentially because of their more serial and systematic search behavior. It also explains why working memory depth benefits may not extend to displays with six and eight items. Participants may simply not have enough time to successfully encode the depth information serially when there are more than four items present. This hypothesis is more consistent with a general benefit of depth to selective attention. It is also possible that depth information aids participants working memory ability more directly, such that on easy trials, depth information is not useful and only provides extraneous information. However, on trials that are just beyond their ability, participants are able to utilize the depth information as a crutch to improve their performance, potentially through some sort of chunking mechanism (Qian et al., 2017). The benefit of this depth information appears to be limited, and does not extend to more challenging trials containing working memory loads beyond than their capacity (e.g., six, eight). This explanation is consistent with previous work conducted by Sarno et al. (2019) and Qian et al. (2017). Further work is required to examine if depth benefits executive function solely via selective attention, or via more task-specific mechanisms (e.g., chunking and working memory).

It is unclear how this deployment of attention may influence inhibitory control. It is possible that the lack of a depth effect was due to participants attempting to encode each arrow serially (including their location in depth), rather than just fixating on the central arrow. In the congruent trials, this resulted in participants being slower in the two-depth plane condition, possibly because they were processing each item's depth. In the one-depth condition, depth was completely irrelevant to the task and therefore did not influence response times. In the incongruent trials it is possible the two different depth conditions elicited similar, and longer, response times but for different reasons. For the one-depth plane-condition, similar to standard flanking tasks, participants were distracted by the flanking information and took longer to respond. However, for the two-depth plane condition, participants may only have been slower due to encoding the relevant depth information rather than being distracted by the incongruent flankers. This hypothesis is consistent with response times being similar in the two-depth plane condition for the incongruent and congruent trials. Participants in this task may always encode the depth information when items are dispersed over multiple depth planes. If this hypothesis is true, participants were also more resilient to the standard flanker effect, since response times did not increase in the incongruent trials compared to congruent trials. Thus, in future studies, if items were further separated in depth or participants were instructed to ignore a specific depth plane, inhibitory control benefits may be more likely to emerge.

Limitations

There were several limitations to the present studies that provide ample opportunity for future research. Specifically, it remains unclear exactly how depth information influences executive functioning. It is possible that depth benefits to various aspects of executive function are at least partially associated with perceptual processing. However, given that the inhibitory control task did not see robust depth benefits, the benefit of depth appears to asymmetrically influence different aspects of executive function. If perceptual processing was the sole cause of the influence of depth, it would likely affect all aspects of executive function. It seems more likely that depth information may influence both perceptual processing and higher order cognitive processing. Additionally, it is challenging to explore components of executive functioning in isolation. Selective attention is likely involved in all three tasks utilized, and it remains unclear if depth information may influence performance in all three components via selective attention abilities. Future work is required to understand *why* executive functioning may be influenced by depth information.

Additionally, there were unexpected findings in the working memory task that present some limitations to the present findings. Specifically, the even-distribution and target-isolated conditions produced the same stimulus arrays for set size 2 (e.g., one cube in the far depth, and one cube in the near depth). However, performance differed for the two conditions, with the even-distribution condition demonstrating poorer accuracy. Given these conditions were identical at set size 2, the difference was likely spurious in nature. Upon the investigation of this hypothesis, it was determined that the difference was due to two low-accuracy trials within the even-distribution condition where the cube changed from blue to purple. When these two trials were omitted from the analysis, there were no differences between the conditions.[1]

Lastly, accuracy in the one-depth-plane condition did not linearly decrease with set size for the high-capacity individuals; performance was poorer for arrays with four items compared to six items. Considering that low-capacity individuals did not demonstrate this same pattern, it is possible that the high-capacity individuals may be employing some sort of depth strategy that is successful for the one-depth-plane condition at set size 6, but not set size 4. It is important to note that even the one-depth-plane condition is presented in depth. The mere presence of depth information may also be influencing performance, relative to the standard two-dimensional change detection tasks. Previous studies, utilizing similar paradigms, have never found these data patterns (e.g., Sarno et al., 2019; Sarno & Neider, 2019). Future work is required to determine if they are consistent with different groups of participants, or if they were artifacts of the specific stimuli in present study. It is important to note that neither of these unexpected findings influence the main questions at hand (i.e., does depth information influence executive functioning broadly?).

Conclusion

Overall, the present studies suggest that depth information can improve some aspects of executive function. These benefits appear to be limited to working memory and selective attention abilities and are specific to the task conditions. Importantly, the depth benefits are also accompanied by consistent depth costs in easier displays (e.g., lower set sizes). Further work is required to understand if inhibitory control can be improved with depth information and if this benefit is also dependent on the task difficulty. Lastly, the exact mechanism underlying depth benefits for executive function remains unclear. Further research is required to determine both *how* and *why* depth information may influence executive function abilities. Until more research is completed, multidimensional displays should be implemented with caution; it remains unclear if the presence of depth information aids more than it hinders executive function.

Data availability None of the data or materials for the experiment reported here is available, and the experiment was not preregistered.

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[1] Working memory results without the two trials: $F(2,58) = 0.91, p = .407, \eta^2 = .03$; one-depth-plane ($M$ = .91, SD = .09), even-distribution (M = .90, SD = .08), target-isolated (M = .89, SD = .09) conditions.

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