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Task manipulation effects on the relationship between working memory and go/no-go task performance☆

Elizabeth A. Wiemers*, Thomas S. Redick

Purdue University, United States

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ABSTRACT

Go/no-go tasks are widely used in psychology as measures of inhibition, mind-wandering, and impulsivity, but relatively little research has explored the impact that task manipulations have on task performance and measurement of the intended psychological constructs. Experiment 1 investigated the differences between perceptual and semantic versions of go/no-go tasks and how task performance relates to individual differences in working memory capacity (WMC), a widely-studied cognitive construct. The type of decision performed on the go/no-go stimuli influenced performance, but not the relationship with WMC. Experiment 2 examined the potential of inter-stimulus interval (ISI), which influenced go/no-go performance, along with the relationships with WMC. However, the type of decision had effects on performance above and beyond that of the ISI. The results are discussed in relation to the psychological literature using go/no-go tasks as behavioral indices of inhibition and mind-wandering, and in the context of previous investigations of individual differences in WMC.

1. Introduction

Cognitive tasks measure performance with the intention of making inferences about the underlying processes involved in completing the task. Attempts have been made to evaluate many processes in this manner such as decision-making, cognitive control, working memory, and attention. Minor adjustments in task structure or performance are used to make inferences about the underlying processes. When consistent performance differences result from specific task manipulations, the intended underlying process is thought to be measured with some degree of reliability and validity. However, a problem arises when considering whether a given task can evaluate the various underlying constructs that are targeted by various researchers. For example, the functionally identical go/no-go task and sustained attention to response task (SART), where a participant is asked to press a button for a certain stimulus/set of stimuli and withhold responses to all other possible stimuli, are used to measure inhibition and mind-wandering, respectively. That is, failure to inhibit a response to a no-go stimulus is discussed as a failure in inhibition (e.g., Diamond, 2013), an instance of mind-wandering (e.g., Robertson, Manly, Andrade, Baddeley, & Yiend, 1997) or a combination of things like attention control and speed/accuracy tradeoff approach (Manly, Davison, Heutink, Galloway, & Robertson, 2000). These concepts are not mutually exclusive, and some consider that more than one mechanism is likely involved. However, these mechanisms are also not entirely

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* Corresponding author at: Department of Psychological Sciences, 703 Third Street, West Lafayette, IN 47909, United States.
E-mail address: ewiemers@purdue.edu (E.A. Wiemers).

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synonymous and are not always considered together. Subsequently, one may offer different explanations or further hypotheses based on the particular interpretation to which they ascribe. Additionally, the critical components of the task may be regarded differently based on these focuses.

Small task manipulations may have large effects on performance. This has important implications for the relationship between the task and the underlying construct it is intended to measure. Thus, two versions of a task may not be assumed to be similarly sensitive to a given process. For example, the comparison between the two-choice and go/no-go paradigms has resulted in striking performance differences. Measso and Zaidel (1990) compared go/no-go and two-choice versions of the lexical decision task, which resulted in substantially faster RTs in the go/no-go task than in the two-choice task when word stimuli were mapped to the go response, but no difference between the tasks when non-words were mapped to the go response. Essentially, participants are asked the same question – whether the item is a word or a non-word, but whether the button press is mapped to the word stimuli or the non-word stimuli affects the speed of responding. This finding illustrates that minor task manipulations that do not have theory-based implications for performance may still affect performance and potentially the way in which the task relates to underlying constructs it was intended to evaluate. This warning is indicative of a wider concern involving the distinction between tasks and underlying processes. The performance measures on a given task may be interpreted differently depending on the goal of the project, and any one task is not a perfect measure of the underlying construct.

In previous research, several task manipulations have been examined in the go/no-go task and the SART, including stimulus modality choice (Nakata, Arakawa, Suzuki, & Nakayama, 2016; Seli, Cheyne, Barton, & Smilek, 2012), task length (McVay & Kane, 2009), and trial type frequency (McVay & Kane, 2012a; Wessel, 2017). There are key differences in these manipulations, all of which had effects on performance. Critically, some task parameters may fundamentally change the way underlying constructs are related to task performance. For example, trial type frequency may be set based on a number of considerations like convenience or total time allotted for the task, if a particular number of no-go trials are needed but time is limited. However, this manipulation could also be considered crucial to the relationship between task performance and underlying constructs. Specifically, the high go-frequency version is used as a measure of sustained attention and response inhibition, but the alternative low go-frequency version minimizes the role of inhibition and emphasizes sustained attention. The idea is that the prepotency of the go response requires inhibition for infrequent no-go trials, which can only occur if the frequency of go trials is disproportionate enough to develop a prepotency for responding. Compared to when go trials occur frequently, go/no-go tasks with relatively few go trials produce much higher *d′* scores, a measure of task sensitivity that accounts for both hit and false alarm rates, slower mean RTs, and increased self-reported mind-wandering (McVay & Kane, 2012a). Comparison of versions with different trial frequencies showed consistent changes relating to trial type frequency such that as no-go frequency increased (20 to 50 to 80%), mean RTs increased on go trials and accuracy increased on no-go trials, although go accuracy remained very high (Jones, Cho, Nystrom, Cohen, & Braver, 2002; Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003; Young, Sutherland, & McCoy, 2018).

1.1. Working memory capacity and the go/no-go task

In addition to these various considerations and task manipulations, a critical factor to consider is working memory capacity (WMC), an individual differences factor that is related to sustained attention and inhibition (Engle & Kane, 2004). This construct is often measured with complex span tasks in which there is a memory component that is interleaved with a processing task. Because the go/no-go task measures inhibition and attention, and WMC is highly related to these constructs, the relationships between specific performance outcomes and WMC are indicative of the way the task relates to the underlying mechanisms it is theorized to measure. However, correlations between WMC and performance on various versions of the go/no-go task are quite variable, a surprising result when compared to the consistency of the relationship between WMC and antisaccade performance, another frequently used inhibition/executive function task (Meier, Smeekens, Silvia, Kwapil, & Kane, 2018). Table 1 shows the variety of relationships between go/no-go performance measures and WMC found in the literature, separated by perceptual (e.g. “3” vs. not “3”) versus semantic (e.g. living vs non-living items) decision types, a distinction that would be expected to affect performance measures but not relationships between performance measures and working memory.

As seen in Table 1, perceptual versions of the go/no-go task are inconsistently related to WMC, despite all but one of these studies (Stawarczyk, Majerus, Catale, & D'Argembeau, 2014) using the same or highly similar WMC measures. Redick, Calvo, Gay, and Engle (2011) found no relationship with WMC in two perceptual versions of the go/no-go task. McVay and Kane (2009) found a similar pattern with the relationship with WMC for the combined tasks, reported in the paper, diminishing when reanalyzed with the perceptual task alone. In unpublished follow-up data by McVay and Kane, reported by Redick et al. (2011), the relationship to WMC was no longer present for the perceptual task. However, Stawarczyk et al. (2014) and Jackson and Balota (2012) found relationships between a perceptual go/no-go task and WMC comparable to those found in semantic tasks. These inconsistent relationships in perceptual versions are focused on the *d′* measure and other accuracy measures. Other WMC relationships are more consistent. As summarized in Table 1, WMC relationships with mean RTs tend to be consistently absent. However, consistent WMC relationships are present with RT (individual standard deviations) ISDs, with high-WMC individuals tending to be less variable in their RTs than low-WMC individuals.

In contrast, relationships in all outcome measures are relatively consistent for semantic versions of the go/no-go task. The same lack of a relationship with mean RTs and a negative relationship with RT ISD is found across semantic tasks. Whereas relationships varied for accuracy measures in the perceptual task, these relationships were invariably positive for semantic tasks. However, comparisons between perceptual and semantic versions are limited by key factors. First, these comparisons are limited by the small number of studies that have included WMC and particularly by the even smaller number that include more than one type of go/no-go

Table 1
Previous WMC & go/no-go studies.

Authors	N	Task	Stimulus Duration	ISI	r			
					No-go ACC	*d′*	RT Mean	RT V
McVay and Kane (2012a)	142	Semantic	250	950	–	0.32	0.04	−0.37
McVay and Kane (2012b)	225	Semantic	300	900	–	0.20	–	−0.17
Unsworth and McMillan (2014)	241	Semantic	300	900	0.12	0.12	–	−0.18
Unsworth and McMillan (2017)	211	Semantic	300	900	0.09	–	0.01	−0.13
Redick et al. (2016)	534	Semantic	300	900	0.21	0.22	0.03	−0.26
Kane et al. (2016)	545	Semantic	300	1500	–	0.18	–	−0.18
McVay and Kane (2009)	83	Perceptual	300	900	–	0.18	–	−0.33
McVay and Kane, (unpublished)	82	Perceptual	300	900	–	−0.05	0.04	−0.15
Stawarczyk et al. (2014)	87	Perceptual	500	2000	0.41	–	−0.15	−0.32
Faneros (2014)	306	Perceptual	300	700	–	0.15	–	–
Marcusson-Clavertz, Cardeña, and Terhune (2016)	111	Perceptual	500	2000	0.00	–	–	−0.02
Morrison, Goolsarran, Rogers, and Jha (2014)	58	Perceptual	250	900	0.06	–	0.14	0.01
Tan et al. (2015)	17	Perceptual	1000	1000	−0.30	–	0.38	0.38
Jackson and Balota (2012), E1	47	Perceptual	200	900	0.18	–	−0.20	−0.04
Jackson and Balota (2012), E2	32	Perceptual	200	900	−0.02	–	−0.17	−0.36

Note: r = correlation with WMC, RT V = Response Time Variability. Redick et al. (2011) Experiments 1 and 2 not listed due to extreme groups design, but no significant WMC differences were found for the perceptual go/no-go task for *d′*, mean RT, or RT ISDs. The RT variability measures are all ISD except Stawarczyk et al. (2014), Faneros (2014), and Marcusson-Clavertz et al. (2016) who reported only coefficient of variation.

task. Second, the differences among the experiments make comparisons between studies even more challenging. For example, Stawarczyk et al. (2014) used a large sample, with a continuous range of WMC scores, and included thought probes intermixed among the go/no-go trials. In contrast, Redick et al. (2011), which did not find a relationship between WMC and go/no-go performance, used an extreme-groups design for WMC, with a small sample size, and no thought probes. Importantly, the unpublished data from McVay & Kane used the same design and participant source as the published semantic data, making the difference in the pattern of WMC relationships more compelling.

There is no clear theoretical reason for the relationship with individual differences in WMC to be different between the perceptual and semantic versions if the task is intended to measure sustained attention or inhibition. Whether the decision is perceptual or semantic, assuming task demands are equal, inhibition and attention should affect performance similarly. To truly investigate this inconsistency, however, the different types of go/no-go must be systematically compared and the respective relationships with WMC must be evaluated.

1.2. Present research

Though many studies have examined the efficacy of the go/no-go task as an inhibition measure and examined the effects of no-go trial frequency on performance, very little has been done to assess the effects of other manipulations in this task. Specifically, two important manipulations have been generally overlooked: stimulus decision type and inter-stimulus interval (ISI). Though many different stimulus versions are used in various tasks, little attention is paid to what effect the choice of stimuli might have on performance. Systematic comparisons of variations of the go/no-go task are generally absent from the literature, with few recent exceptions (Wessel, 2017; Young et al., 2018), despite such manipulations having potential implications for what the task is measuring. This absence in the literature raises the question – how different is too different? Given that other task manipulations can have such large effects on performance, it follows that task- and decision-type manipulations may also have large effects. After determining what effects there are, the question becomes whether performance on the various versions can be interpreted the same way, and how these differences in performance relate back to individual differences. That is, if differences between perceptual and semantic versions of go/no-go tasks have large effects on performance to the extent that there are varied relationships with individual differences in WMC, the tasks may be measuring fundamentally different underlying processes, or measuring them to very different extents. Thus, the decision to use a perceptual or semantic SART is not trivial, and may have important consequences.

The objective of the current research is to determine whether particular manipulations alter the way in which the go/no-go task relates to the underlying constructs the task is intended to measure, and why. The present studies systematically compared perceptual and semantic versions of the go/no-go task with task-type, decision-type, and ISI manipulations. Whereas most inhibition studies focus exclusively on false alarms on rare no-go trials, the present work additionally evaluated mean RTs and RT ISDs for go trials, as many mind-wandering studies do when using SART. In addition, we investigated how each of these go/no-go dependent variables relates to WMC.

Based on the literature, performance on the perceptual tasks was expected to be better, overall, than performance on the semantic tasks in the form of faster mean RTs, smaller RT ISDs, higher no-go accuracy rates, and higher *d′* values. Predictions about how the perceptual and semantic go/no-go versions in the first set of experiments (E1a-c) would be related to WMC were informed by the literature summarized in Table 1.

Initially, the present work was influenced by Redick et al. (2011), who found no relationship between WMC and perceptual go/no-go performance, and Redick et al. (2016), who found a moderate relationship between WMC and semantic go/no-go performance. Further searching in the literature showed that these inconsistencies were found across other studies, too, which are summarized in Table 1. Experiment 1 attempted to determine the task distinctions among various types of semantic and perceptual go/no-go tasks used in these studies that could explain this pattern. After concluding Experiment 1 without a satisfactory explanation for the pattern in the literature, and while recognizing again that the previous studies vary along a number of dimensions that could influence the relationship with WMC, Experiment 2 was planned to investigate another such dimension. The current research is the first to systematically manipulate the go/no-go task to examine the effects on both performance and relationships with WMC.

2. Experiment 1A

In Experiment 1a (E1a), semantic and perceptual go/no-go tasks using the same pool of stimuli are compared within subjects to determine what effect the decision made during a go/no-go task has on various measures of performance and their relationship with individual differences in WMC. The semantic task was planned to be similar to the semantic versions of the go/no-go task in the literature, while being able to directly compare with the perceptual version created to go with it.

2.1. Method

2.1.1. Participants

Purdue University students enrolled in an introductory psychology course participated in this study for course credit. Of the total 123 participants, 3 were excluded for extremely poor go performance, which was considered less than 80% accurate on go trials, and 14 were excluded for extremely poor no-go performance, which was considered less than11% accurate on no-go trials. Additionally, 1 participant was excluded for having an above-threshold (20%) percent of errors on math for operation span. These constraints left 105 participants in the analyzed sample. All analyses were also conducted on the full sample; for this and subsequent experiments, differences in the results of the analyses are provided in the Supplemental materials.

2.1.2. Tasks

Operation span (Redick et al., 2012; Unsworth, Heitz, Schrock, & Engle, 2005). This verbal working memory capacity measure alternates presenting letters to be remembered and math problems to solve. Participants indicate whether a number shown is the correct answer to the equation that had been presented on the previous screen. Participants are then shown a letter and then another math problem. The pattern repeats for 3–7 items before a recall screen appears. With three presentations of each set length, there are a total of 75 items to recall. The partial scoring method is used such that any letter recalled in the correct serial position results in a point regardless of whether the rest of the set is correct.

Symmetry span (Redick et al., 2012; Unsworth, Redick, Heitz, Broadway, & Engle, 2009). This spatial measure of working memory capacity is similar in structure to operation span but uses symmetry judgements in place of math problems and locations of red squares in a grid instead of letters. Participants respond 'yes' or 'no' to whether the image on the previous screen was symmetrical about a vertical line and are then shown a 4 × 4 grid with one block colored red. Another image follows and this pattern continues until 2–5 red squares have been presented. A blank grid is presented for recall and participants click the locations in the order they appeared. Partial scoring is used for this task as well, with each set size randomly appearing three times for a total possible score of 42.

Semantic go/no-go – non-living. Participants were shown a word that was either an exemplar from the "living" category or "non-living" category based on a word list created for this study (available in supplemental materials). Participants were to press the spacebar if and only if the word shown was an exemplar of the "non-living" category. Each participant saw 240 go (non-living) trials and 30 no-go (living) trials in a random order. This go/no-go frequency is similar to that used in the SART (Robertson et al., 1997). Half of each of the go and no-go stimuli were presented in uppercase letters and the other half were presented in lowercase letters. No items were repeated during the task. Words were shown for up to 300 ms before a row of uppercase X's was presented as a mask for 900 ms. Participants were allowed to press the spacebar anytime within those 1200 ms. If the participant responded within the first 300 ms when the stimulus was still on-screen, the program advanced to the mask. If the participant responded during the mask, the program still did not move on until the 900 ms passed. The next stimulus was immediately presented after the mask. See Fig. 1 for the task structure.

Perceptual go/no-go – case. This task was similar to the task described above, including the use of living and non-living words in both uppercase and lowercase presentations. The difference is that participants were asked to press the spacebar if and only if the word was presented in all uppercase letters if they were in group A or if and only if the word was presented in all lowercase letters if they were in group B. As such, the number of exemplars from each category is also different. Here, there were 240 go trials (uppercase/lowercase) and 30 no-go (lowercase/uppercase), and half of each of the go and no-go lists came from the 'living' word list and the other half came from the 'non-living' word list. No words were repeated between or within tasks. Though repeating stimuli is common in the literature, stimuli were deliberately not repeated in this study to eliminate the possibility that performance in latter trials would be influenced by previous stimulus-response associations from earlier trials in the experiment (Verbruggen & Logan, 2008).

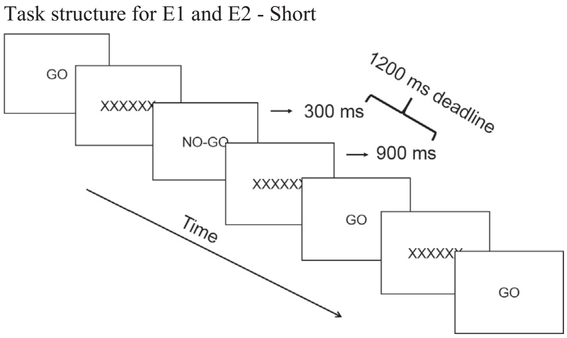

Fig. 1A. Task structure for E1 and E2 - Short.

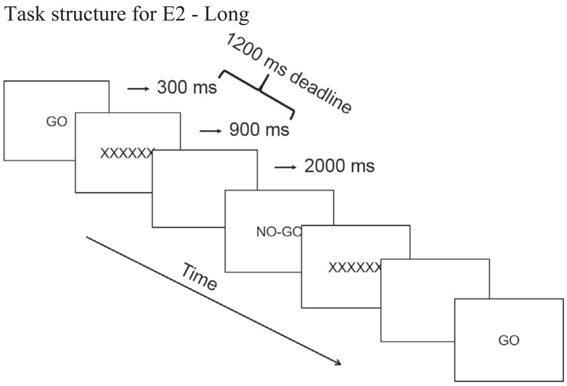

Fig. 1B. Task structure for E2 - Long.

2.1.3. Procedure

Between 1 and 3 participants were simultaneously run in a computer lab and quietly given individual instruction before each task. Participants signed a consent form and then filled out a brief demographic survey. Then, the operation span and symmetry span were completed, in the same order for all subjects. After the working memory tests, participants completed the go/no-go task. Half the participants completed the semantic version and then the perceptual version of the task and the other half of the participants completed the tasks in the opposite order. Within each order, half of the participants completed the uppercase version of the perceptual task as described above and the other half completed the lowercase version of the task as described above. Because this experiment included both a semantic and a perceptual version of the task including two versions of the perceptual task, within- and between-subjects comparisons were examined. The session was typically completed in 45 min.

2.1.4. Analyses

ANCOVAs were used to evaluate differences in *d′*, *C*, mean RTs, and RT ISDs.[1] Between-subjects variables include version of the perceptual task (uppercase or lowercase) and order (perceptual first or semantic first). Composite WMC scores, the average of the z-scores from each task, were the between-subjects covariate. The within-subjects variable is task type (perceptual vs. semantic) for all analyses.

Sensitivity, *d′*, is used to report accuracy in a way that accounts for both hits and false alarms (Stanislaw & Todorov, 1999). A logarithmic adjustment was used to ensure the formula would work even where no errors occurred. This adjustment involved adding 0.5 to every individual's total number of correct trials for both go and no-go trials and dividing by *n* trials + 1. To accompany this measure, *C*, a measure of bias, was also calculated.

For the RT analyses, we used non-transformed variables to allow close comparison to the literature we are investigating. However, it must be noted that RTs often have non-normal distributions, and therefore the raw RTs may not be ideal for ANCOVAs (Van Zandt & Townsend, 2013). We repeated our analyses using log-transformed RTs for both mean and ISD analyses. We found minimal differences in the results, which we report in the Supplemental Materials.

Correlations were used to evaluate relationships between WMC and *d′*, *C*, RT means, and RT ISDs. All skewness and kurtosis values were within acceptable limits, with the largest absolute value at 1.2 for skewness and 2.7 for kurtosis across this and all subsequent studies. All *p*-values discussed as significant are less than 0.05.

[1] Accuracy for go and no-go trials is reported and analyzed in the supplemental materials. These analyses help specify the effects observed in the sensitivity and bias measures.

Table 2
E1 descriptive statistics.

	E1a			E1b		E1c	
	Upper	Lower	Non-living	Non-3	Non-X	Only 3	Living
Ospan *M* (SD)		59.58 (10.73)		56.97 (13.53)		60.25 (9.75)	
Sspan *M* (SD)		30.99 (6.46)		30.14 (7.35)		31.07 (7.38)	
d′ *M* (SD)	2.80 (0.77)	2.44 (0.88)	2.32 (0.81)	2.68 (1.03)	2.61 (1.02)	2.88 (0.89)	2.00 (0.68)
C *M* (SD)	−1.06 (0.35)	−1.10 (0.29)	−1.08 (0.31)	−1.04 (0.30)	−1.19 (0.35)	−1.03 (0.27)	−0.90 (0.33)
Go Mean RT *M* (SD)	405 (89)	413 (84)	509 (87)	397 (106)	402 (105)	383 (92)	576 (93)
Go RT ISD *M* (SD)	113 (37)	116 (32)	137 (34)	108 (42)	106 (41)	109 (41)	142 (33)

Note: Ospan = Operation span, Sspan = Symmetry span, RT = response time, ISD = individual standard deviation, WMC = working memory capacity.

2.2. Results

Note that while each of the 105 participants saw both semantic and perceptual tasks, the groups for the versions of the perceptual task were 56 participants for the uppercase letters group and 49 participants for the lowercase letters group. The following section reviews these comparisons in terms of both accuracy and RTs after a brief report of WMC measures. Descriptive statistics are summarized in Table 2, and all ANCOVA main effects and interactions are reported in Tables 3–6.

2.2.1. WMC measurement

Participants performed very similarly to normed samples (Redick et al., 2012) for both operation and symmetry span (Table 2). The two are correlated ($r = 0.45$, $p < .001$), justifying the composite score used in all further analyses.

2.2.2. Sensitivity and bias

As shown in Table 3 and Fig. 2A, the *d′* measure was significantly greater for the perceptual task than the semantic task. This effect also interacted with version of the perceptual task such that *d′* was higher for uppercase in the perceptual version compared to lowercase and semantic versions. Additionally, there was a main effect of WMC, which was correlated with *d′* in both the perceptual ($r = 0.32$, $p < .01$) and semantic ($r = 0.27$, $p < .01$) tasks. However, it is of note that when split by version, WMC was correlated significantly with *d′* on the perceptual task for the uppercase version ($r = 0.44$, $p < .01$) but not the lowercase version ($r = 0.22$, $p = .13$).

For bias, *C*, there was no main effect of task, WMC, order, or version. Fig. 2B shows very consistent bias across E1a. There were also no significant interactions between any of the variables (Table 4).

Table 3
ANCOVA output – *d′* E1.

	E1a			E1b			E1c		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Main Effects									
Task	20.28	< 0.001	0.17	0.78	0.379	0.01	122.19	< 0.001	0.55
WMC	12.65	0.001	0.11	9.04	0.003	0.08	6.11	0.015	0.06
Order	0.74	0.391	0.01	0.77	0.383	0.01	0.28	0.600	0.00
Version	1.74	0.190	0.02	–	–	–	–	–	–
2-Way Interactions									
Task × WMC	0.64	0.424	0.01	0.45	0.505	0.01	0.26	0.609	0.00
Task × Order	0.03	0.860	0.00	0.01	0.918	0.00	2.66	0.106	0.03
Task × Version	6.78	0.011	0.06	–	–	–	–	–	–
Order × Version	0.00	0.979	0.00	–	–	–	–	–	–
3-Way Interactions									
Task × Version × Order	0.91	0.342	0.01	–	–	–	–	–	–

Note: Task = Go/No-go type, Order = semantic first vs. perceptual first, Version = uppercase vs. lowercase as the go stimulus within perceptual task. WMC is a continuous variable used as a covariate in these analyses.

Table 4
ANCOVA output – *C* E1.

	E1a			E1b			E1c		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Main Effects									
Task	0.03	0.873	0.00	33.42	< 0.001	0.25	14.78	< 0.001	0.13
WMC	2.75	0.100	0.03	0.92	0.341	0.01	0.10	0.753	0.00
Order	0.27	0.603	0.00	0.41	0.523	0.00	0.61	0.437	0.01
Version	0.02	0.902	0.00	–	–	–	–	–	–
2-Way Interactions									
Task × WMC	0.13	0.717	0.00	0.92	0.339	0.01	0.79	0.376	0.01
Task × Order	1.86	0.226	0.02	0.01	0.928	0.00	0.25	0.617	0.00
Task × Version	1.43	0.235	0.01	–	–	–	–	–	–
Order × Version	0.71	0.401	0.01	–	–	–	–	–	–
3-Way Interactions									
Task × Version × Order	0.38	0.538	0.04	–	–	–	–	–	–

Note: Task = Go/No-go type, Order = semantic first vs. perceptual first, Version = uppercase vs. lowercase as the go stimulus within perceptual task. WMC is a continuous variable used as a covariate in these analyses.

Table 5
ANCOVA Output – Mean RT E1.

	E1a			E1b			E1c		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Main Effects									
Task	214.81	< 0.001	0.68	0.81	0.369	0.01	444.57	< 0.001	0.82
WMC	3.66	0.059	0.04	1.49	0.224	0.02	0.09	0.762	0.00
Order	1.35	0.249	0.01	0.18	0.675	0.00	0.33	0.567	0.00
Version	0.11	0.736	0.00	–	–	–	–	–	–
2-Way Interactions									
Task × WMC	0.10	0.759	0.00	3.31	0.072	0.03	1.13	0.290	0.01
Task × Order	20.65	< 0.001	0.17	2.27	0.135	0.02	7.26	0.008	0.07
Task × Version	0.02	0.904	0.00	–	–	–	–	–	–
Order × Version	0.31	0.579	0.00	–	–	–	–	–	–
3-Way Interactions									
Task × Version × Order	2.40	0.125	0.02	–	–	–	–	–	–

Note: Task = Go/No-go type, Order = semantic first vs. perceptual first, Version = uppercase vs. lowercase as the go stimulus within perceptual task. WMC is a continuous variable used as a covariate in these analyses.

Table 6
ANCOVA output – RT ISDs E1.

	E1a			E1b			E1c		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Main Effects									
Task	36.10	< 0.001	0.27	0.30	0.585	0.00	50.43	< 0.001	0.34
WMC	11.02	0.001	0.10	1.16	0.284	0.01	18.11	< 0.001	0.16
Order	0.06	0.806	0.00	0.08	0.775	0.00	0.73	0.395	0.01
Version	0.58	0.449	0.01	–	–	–	–	–	–
2-Way Interactions									
Task × WMC	0.48	0.491	0.01	0.01	0.929	0.00	0.02	0.890	0.00
Task × Order	15.01	< 0.001	0.13	0.25	0.617	0.00	2.71	0.103	0.03
Task × Version	0.25	0.620	0.00	–	–	–	–	–	–
Order × Version	0.06	0.806	0.00	–	–	–	–	–	–
3-Way Interactions									
Task × Version × Order	0.87	0.354	0.01	–	–	–	–	–	–

Note: Task = Go/No-go type, Order = semantic first vs. perceptual first, Version = uppercase vs. lowercase as the go stimulus within perceptual task. WMC is a continuous variable used as a covariate in these analyses.

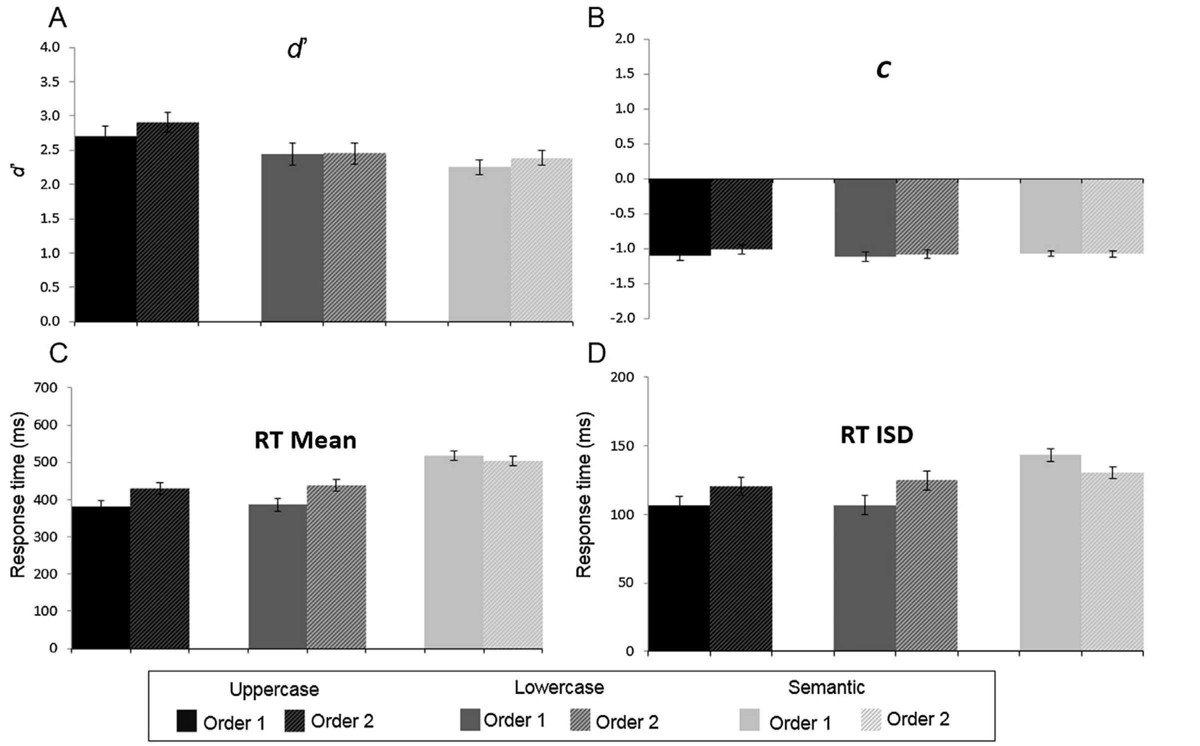

Fig. 2. Results from E1a. (A) *d′*, (B) *C*, (C) mean RT, and (D) RT ISD; error bars are ± 1 standard error of the mean. For order, 1 = Perceptual task first, 2 = Semantic task first.

2.2.3. Response times

As expected, participants were significantly faster on the perceptual task than the semantic task. This difference can be seen in Fig. 2C. Although there was no main effect of order, there was an interaction between task and order driven by responses to the perceptual task being faster if the perceptual task came first ($M = 385$, $SD = 69$) than if the perceptual task came second ($M = 432$, $SD = 91$). There were no effects or interactions involving version of the perceptual task in relation to mean RTs. There were no significant effects involving WMC.

Participants were significantly less variable on the perceptual task than the semantic task, as is evident in Table 6 and Fig. 2D. In line with the mean RTs, there was no main effect of order for the RT ISDs, but there was an interaction such that the participants were less variable on the perceptual task when the perceptual task was first. Again, there were no effects or interactions involving version of the perceptual task in regard to RT ISDs. There was a main effect of WMC on RT ISDs, with higher WMC associated with lower RT ISDs for both perceptual ($r = -0.23$, $p = .02$) and semantic tasks ($r = -0.28$, $p < .01$). However, similar to the mean RTs, there were no interactions involving WMC.

2.3. Discussion

The goal of E1a was to directly compare perceptual and semantic decisions on the go/no-go task by using the same stimuli and a within-subjects design. In addition, the perceptual task had two decision versions. Some participants mapped uppercase words to the go response and the others mapped lowercase words to the go response. For the primary comparison between semantic and perceptual tasks, several differences emerged. On the perceptual task versus the semantic task, the participants were faster and less variable on go trials, and produced higher *d′* values. The combination of higher accuracy and faster RTs indicates that the performance differences are not due to a speed-accuracy tradeoff, as found in comparisons of stimulus modality (Seli et al., 2012). The slower RTs and lower accuracy on the semantic task despite using the same stimuli as the perceptual task indicates that something about the decision, rather than the specific stimuli, is causing a difference in performance.

Comparing the versions of the perceptual task to each other allows evaluation of performance based on the specific decision within task type. Differences in uppercase versus lowercase versions of the perceptual tasks emerged in *d′* with *d′* being higher for the uppercase version than the lowercase version, though with no difference in the semantic task, this did not lead to a main effect of version (uppercase vs lowercase), only an interaction with task (perceptual vs semantic). This unexpected result may be a function of the mask, a string of capital X's, being similar to the uppercase words. Therefore, when the uppercase words are the frequent go stimulus, a different goal of "did the letters change height" may become the easier goal to keep in mind. However, the same does not occur when the frequent go stimuli are lowercase words as they would be consistently changing from the mask and the infrequent

Table 7
Correlations with WMC E1.

	E1a			E1b		E1c	
	Upper	Lower	Non-living	Non-3	Non-X	Only 3	Living
N =	56	49	105	101		102	
Correlations							
d'	0.44*	0.22	0.27*	0.24*	0.30*	0.21*	0.20*
C	0.14	0.10	0.17	0.06	0.12	0.09	−0.02
Mean RT	0.13	0.16	0.18	0.06	0.17	0.05	−0.09
RT ISD	−0.19	−0.29*	−0.28*	−0.10	−0.10	−0.26*	−0.36*
Reliabilities							
Mean RT	0.86	0.82	0.84	0.89	0.91	0.81	0.86
RT ISD	0.77	0.76	0.76	0.76	0.80	0.67	0.81

Note: * indicates $p < .05$, reliabilities given for item level accuracy (Cronbach's alpha) and split half RT measures (Spearman-Brown), the d' measure is calculated from summary variables and does not lend itself to reliability estimates.

uppercase words may be less salient. If this were the case, differences might be expected in the RTs, but they are only present in d'.

In addition, the observed order effect indicated that when the perceptual task was first, participants' responses were faster and less variable than on the semantic task. However, when the perceptual task was after the semantic task, performance on the perceptual task looked more similar to the performance on the semantic task. This suggests that the processing of the semantic task may influence how the perceptual task is completed. It is possible that it is easier to ignore the semantic element of the stimuli when asked to focus on the perceptual aspects first and more difficult to do so when asked to first evaluate the semantic aspect. Interestingly, the order had no effect on performance for the semantic task, so the interference seems to be specifically from semantic to perceptual. If replicated, the implication for studies using multiple go/no-go tasks indicates an asymmetric order effect.

The semantic task correlations with WMC (Table 7) were largely consistent with previous work (Table 1), especially those studies using WMC and semantic go/no-go tasks very similar to the current work (Kane et al., 2016; McVay & Kane, 2012a, 2012b; Redick et al., 2016; Unsworth & McMillan, 2014, 2017). However, emblematic of the previous literature examining individual differences in WMC and go/no-go performance, the WMC correlations involving the perceptual go/no-go tasks were mixed. Significant positive correlations between WMC and d' were observed with the semantic and perceptual tasks. Consistent with previous research, no significant relationships between WMC and mean RTs on the perceptual or semantic task were observed. The WMC correlation with RT ISDs was significant for the semantic task and the lowercase version of the perceptual task, but not for the uppercase version of the task. However, it is important to note that the significance of the perceptual go/no-go correlations are influenced by the fact that the sample sizes are roughly half the size of the semantic go/no-go task, where the whole sample is used.

3. Experiment 1B

Although the semantic go/no-go results in E1a were in line with predictions and similar to previous work, the perceptual go/no-go results continued the trend of producing unexpected and mixed results regarding relationships with individual differences in WMC. Two additional perceptual versions of the go/no-go task were used in Elb to investigate whether the stimuli and decision within perceptual versions affects performance on the tasks. Whereas the perceptual tasks in E1a were designed to be closely comparable to the semantic task in E1a, the perceptual tasks in E1b were designed to be closely comparable to the perceptual versions more frequently used in the literature. Because both tasks were perceptual, we had no strong predictions about differences in performance between the two tasks. Based on Redick et al. (2011), we would predict that WMC would be unrelated to any of the go/no-go dependent variables; in contrast, based on Stawarczyk et al. (2014), we would predict WMC to be positively related to no-go accuracy, which would likely result in a relationship with d' (not reported in that study), and negatively related to RT ISDs. Based on E1a, we would predict WMC to be positively related to d' and unrelated to mean RT. The prediction for RT ISD is less clear because the lowercase perceptual task was significantly correlated with WMC, but the uppercase perceptual task was not.

3.1. Method

3.1.1. Participants

Participants for E1b were recruited from the same subject pool as E1a but had not participated in E1a. Of the 109 participants, 2 were excluded for extremely poor go performance and 6 were excluded for extremely poor no-go performance, using the same cutoffs described in E1a. The remaining 101 are included in the analyses reported in the main text.

3.1.2. Tasks

Operation span. This task was the same as in E1a.

Symmetry span. This task was the same as in E1a.

Perceptual go/no-go – digits. This task was similar to the go/no-go tasks described in E1a. However, instead of word stimuli, the digits 0 through 9 appeared randomly. Participants were asked to press the spacebar as quickly as possible if and only if the digit was not a 3. This specific version of the task is common in the literature as it closely resembles the SART originally described by Robertson et al. (1997).

Perceptual go/no-go – letters. This task was similar to the task described above. However, instead of digits, letters from the English alphabet were presented. Participants were asked to press the spacebar if and only if the letter was not an X. The non-X letters were B, C, D, G, H, J, L, M, N, P, Q, R, T, V, and Z. Of note, despite similarity to the no-go stimulus, the same mask consisting of 12 capital X's was used. This was done to be consistent with the other tasks in this series of experiments.

3.1.3. Procedure

This study was administered mostly as described in E1a. The program still chose the order in which the letter and digit go/no-go tasks appeared based on the subject number entered. This procedure resulted in two groups, with one group completing the letters task before the digits task and the other group completing the digits task before the letters task.

3.1.4. Analyses

The analyses were very similar to E1a, except there was no version variable in E1b.

3.2. Results

Of the 101 participants included in the analyses, 49 completed the digits task first and the other 52 completed the letters task first. Descriptive statistics for the outcome measures are reported in Table 2.

3.2.1. WMC measurement

Participants performed very similarly to normed samples for both Operation Span and Symmetry Span (Table 2). The two were correlated ($r = 0.45$, $p < .001$), justifying the composite score used in all further analyses.

3.2.2. Sensitivity and bias

The *d′* measure was not significantly different between the two tasks, as can be seen in Fig. 3A. However, there was a significant main effect of WMC which was significantly correlated with *d′* for both the digits ($r = 0.24$, $p = .01$) and letters ($r = 0.30$, $p < .01$) tasks. As Table 3 shows, there were no significant effects or interactions involving order for *d′*.

In regard to bias, *C*, there was a main effect of task, such that there was a stronger go-bias or likelihood of pressing the button, during the letters task versus the digits task. There were no other significant effects or interactions (Table 4and Fig. 3B).

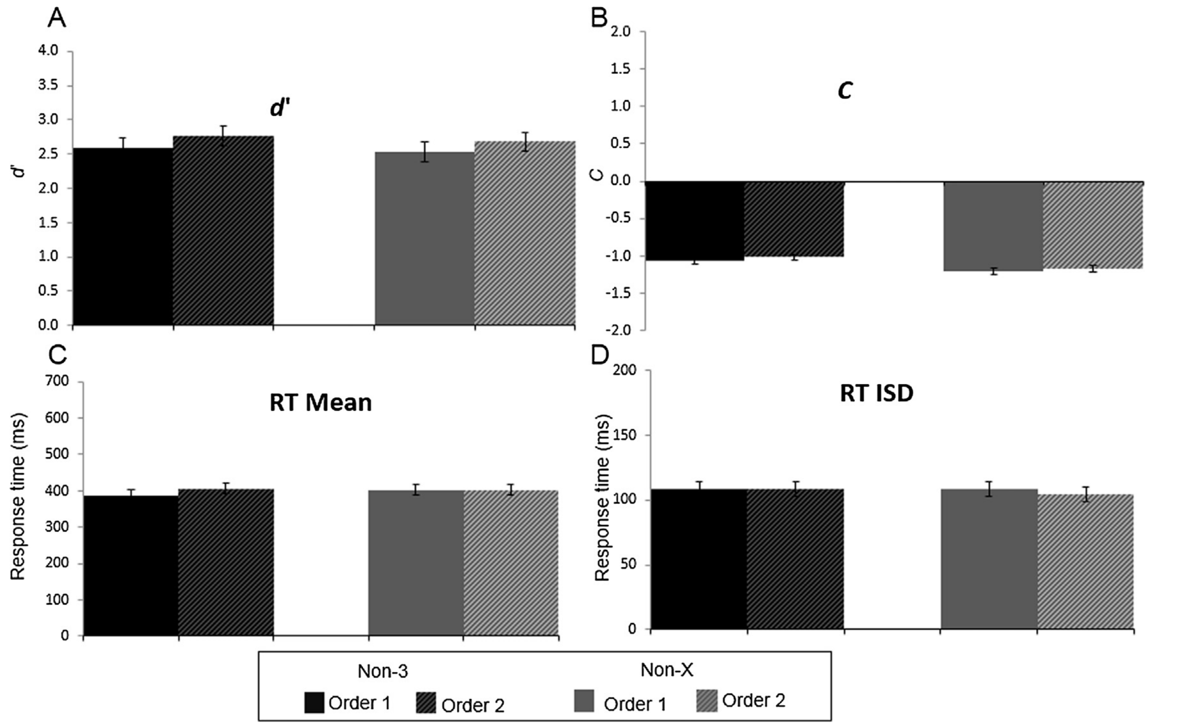

Fig. 3. Results from E1b. (A) *d′*, (B) *C*, (C) mean RT, and (D) RT ISD; error bars are ± 1 standard error of the mean. For order, 1 = Non-3 task first, 2 = Non-X task first.

3.2.3. Response times

Mean RTs were not significantly different between the tasks, as shown in Table 5 and Fig. 3C. There was also no main effect of WMC and no interactions involving WMC. There were no effects or interactions involving order for mean RTs. Additionally, there were no significant main effects or interactions for RT ISDs, as shown in Table 6 and Fig. 3D.

3.3. Discussion

The goal for E1b was to evaluate two additional perceptual versions that were more similar to those frequently used in the literature. This was done to compare different perceptual decisions to each other to evaluate whether the performance differences were specific to a semantic/perceptual comparison, or if performance differences would be a function of any different decision. There were no significant differences between the tasks for mean RT, RT ISD, or *d′*, indicating that performance was largely consistent between the two tasks. However, *C* was significantly higher (less negative) in the digits versus the letters task, which indicates a weaker go-bias in the digits task than the letters task.

In addition to comparing the tasks to each other, relationships with WMC were examined (Table 7). For both perceptual tasks, significant correlations between WMC and *d′* were observed, but WMC was not significantly correlated with mean RT or RT ISD in either task. The relationship to *d′* is inconsistent with Redick et al. (2011), who found no relationship between WMC and *d′* despite having a task very similar to the letters task in the present study. The lack of associations between WMC and RT measures were more consistent with the literature, including Redick et al. (2011), and were consistent with E1a. Of note, no-go accuracy in Redick et al. (2011) was considerably higher than in the letter go/no-go task in E1b (see Supplemental Table 1). There are a few task parameters that differ between Redick et al. (2011) and the current work that could have contributed to these differences in outcome variables. In Redick et al. (2011), there was no mask after stimulus presentation, and there was a fixation cross before each stimulus that when added to the blank ISI, makes the total ISI longer (700 ms ISI + 1000 ms fixation) than in the current experiment (900 ms mask). These collective results indicate that while go/no-go performance is generally similar between the different perceptual versions used in Ela and Elb, something about the task design may still affect performance and corresponding relationships with individual differences variables such as WMC.

4. Experiment 1C

Like E1a, E1c compares semantic and perceptual go/no-go tasks within subjects, without holding the stimuli the same between the two versions. Critically, and analogous to the manipulation by Measso and Zaidel (1990) and Redick et al. (2011), participants were instructed to make a go response based on the value that was the no-go stimulus set in E1a and E1b. For example, in the semantic task in E1a, participants made go responses to non-living exemplars and no-go responses to living exemplars; in E1c, go and no-go responses were mapped to living and non-living words, respectively. This demonstrates the applicability of these findings to the wider literature using different versions by determining whether the same patterns hold.

4.1. Method

4.1.1. Participants

Again, students from the same subject pool who had not participated in E1a or E1b were recruited for this study. A total of 128 participated, though 13 were not included in the analyses due to poor go performance and 12 were not included due to poor no-go performance the go/no-go tasks. Additionally, 1 participant was excluded due to above threshold math errors on the operation span task, using the same cutoffs described in E1a. The remaining 102 participants were included in all analyses reported in the main text.

4.1.2. Tasks

Operation span. This task was the same as in E1a and E1b.

Symmetry span. This task was the same as in E1a and E1b.

Go/no-go – digits. This task was the same digits go/no-go task described in E1b. However, the task decision was switched such that participants pressed the spacebar if and only if the digit was a 3, not pressing the spacebar if the digit was not a 3. Note this is the only go/no-go task used thus far where one specific stimulus ('3') was mapped to the go response, which may be predicted to reduce the working memory demands of the task, leading to both more accurate and faster task performance (Young et al., 2018).

Semantic go/no-go – living. This task was the same semantic go/no-go task described in E1a. However, the task decision was switched such that the participant was asked to press the spacebar if and only if the stimulus was a living item, and avoid pressing the spacebar if the stimulus was a non-living item.

4.1.3. Procedure

This study was very similar in structure to E1b. The semantic and perceptual order was counterbalanced across subjects, again resulting in two groups. WMC was again continuous and between subjects.

4.1.4. Analyses

The analyses were the same as E1b.

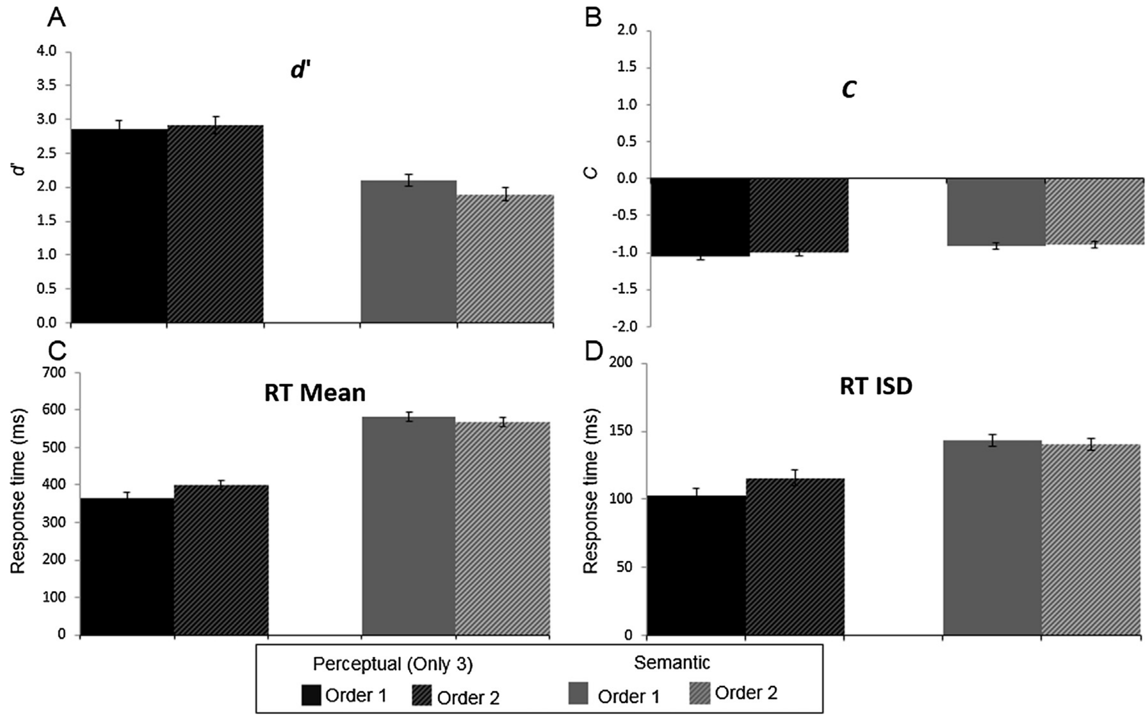

Fig. 4. Results from E1c. (A) *d′*, (B) *C*, (C) mean RT, and (D) RT ISD; error bars are ± 1 standard error of the mean. For order, 1 = Perceptual task first, 2 = Semantic task first.

4.2. Results

Of the 102 participants included in the analyses, 48 completed the perceptual task first and the other 54 completed the semantic task first. Descriptive statistics for the outcome measures are provided in Table 2.

4.2.1. WMC measurement

Participants performed very similar to normed samples for both Operation Span and Symmetry Span (Table 2). The two are correlated ($r = 0.51$, $p < .001$), justifying the composite score used in all further analyses.

4.2.2. Sensitivity and bias

The *d′* measure was again greater for the perceptual task than the semantic task, as shown in Fig. 4A. Additionally, there was a main effect of WMC, which was significantly correlated with *d′* in both the perceptual ($r = 0.21$, $p = .03$) and semantic ($r = 0.20$, $p = .047$) tasks. As Table 3 shows, there were no significant effects or interactions involving order for *d′*.

For bias, *C*, there was a significant main effect of task such that there was a strong go-bias for the perceptual versus the semantic task. As shown in Table 4 and Fig. 4B, there were no other significant effects or interactions.

4.2.3. Response times

Again, participants were faster on the perceptual task than the semantic task. There was no significant main effect of order, but there was a significant task by order interaction due to participants being faster on the perceptual task when the perceptual task was the first task completed ($M = 367$, $SD = 72$) compared to when the perceptual task was the second task completed ($M = 401$, $SD = 109$). There were no significant effects or interactions involving WMC for mean RTs, as seen in Table 5 and Fig. 4C.

RT ISDs were more variable for the semantic task than the perceptual task, as seen in Fig. 4D. There was also a main effect of WMC, which significantly correlated with both perceptual ($r = -0.26, p < .01$) and semantic ($r = -0.36, p < .01$) tasks. However, as Table 6 shows, there were no significant interactions involving WMC or order with RT ISDs.

4.3. Discussion

The perceptual/semantic comparison in E1c closely replicated E1a with perceptual performance being faster, less variable, and producing higher *d′* scores than the semantic task. This, again, shows that something about the specific decision made during the task is influencing task performance. In addition, the order of the tasks again affected mean RTs such that responses to the perceptual task were slower when the semantic task had been completed prior to the perceptual task. However, the semantic task, as in E1a, was unaffected by the order of the tasks. Again, this pattern suggests that the semantic quality of the stimuli may be easier to ignore if the first task does not include a semantic decision, but more difficult to ignore when the semantic aspect had previously been the focus. Slightly different from E1a are the results for *C*, which show a main effect of task where there was no effect in E1a. The difference in E1c is such that there is a stronger go bias for the perceptual task than the semantic task.

In regard to WMC, and again in line with the literature, E1a, and E1b, the correlation with mean RT was not significant (Table 7). Similar to E1a and E1b, relationships with *d′* were found in both tasks in E1c. Also, similar to E1a, relationships were found with RT ISDs for both tasks. Previous studies have repeatedly shown no significant relationships with mean RTs, as is replicated across all six tasks in E1. The literature shows more varied relationships between WMC and *d′* and between WMC and RT ISDs, especially for perceptual go/no-go tasks. In E1, significant correlations between WMC and *d′* are consistently observed for both semantic and perceptual go/no-go tasks. The WMC correlations with RT ISDs are significant in the semantic tasks (E1a, E1c; Table 1), but less consistently observed in the perceptual tasks (E1a, E1b, E1c; Table 1).

5. Experiment 2

In the literature and E1, semantic task outcomes are related to WMC with some regularity: usually, mean RT is not correlated with WMC, whereas *d′* is positively correlated and RT ISD is negatively correlated. In contrast, perceptual task outcomes related to WMC are much less consistent (Tables 1 and 7). E1 examined the possibility that this distinction had something to do with the task or decision types. The results in E1 show limited support for this possibility. Rather, the results of E1 suggest that additional task factors are likely influencing this pattern. The goal of Experiment 2 (E2) was to experimentally induce a difference in the relationships between WMC and go/no-go outcomes.

As can be seen in Table 1, the semantic tasks used in the literature were also more consistently structured than perceptual tasks. Specifically, all tested semantic versions, including the two from E1, had relatively short ISIs with a mask appearing for the length of the interval. However, the perceptual tasks, not including E1, had more variable and longer ISIs usually composed of a blank screen or a mask with an additional blank screen following (e.g., Redick et al., 2011; Stawarczyk et al., 2014; Tan, Zou, Chen, & Luo, 2015). Additionally, the stimulus presentation lengths tend to be longer for the perceptual versions, further adding to the time from the onset of one stimulus to the onset of another.

Previous research has shown that variation in the ISI in go/no-go tasks affects task performance and its relationship with ADHD (Metin, Roeyers, Wiersema, van der Meere, & Sonuga-Barke, 2012). It is possible that the variation in ISI also influences how dependent variables from the go/no-go task are related to individual differences in WMC. This would follow from the literature showing different ISIs resulting in performance differences on various tasks, especially involving mind-wandering outcomes. For example, De Jong, Berendsen, and Cools (1999) found short ISIs produced a smaller Stroop effect despite being only 1800 ms faster than the long ISI (see also Jackson & Balota, 2013; Parris, 2014). Short ISIs also led to faster RTs in go/no-go studies, and usually coincided with lower accuracy on no-go trials (Jackson & Balota, 2012; Smallwood et al., 2004; Zamorano et al., 2014). Additionally, Jackson and Balota (2012) found increases in mind-wandering self-reports in the longer ISI version (Experiment 3) compared to the short ISI condition (Experiment 1). Of note, all of the go/no-go studies examining the role of ISI used perceptual versions of the task.

One potential explanation is that the longer ISIs are less demanding cognitively, and therefore invite more mind-wandering or lapses of attention to occur (De Jong et al., 1999; Thomson, Besner, & Smilek, 2015). This could lead to a stronger relationship with working memory as the need to inhibit mind wandering and enact cognitive control to stay on task becomes greater (Unsworth, Redick, Lakey, & Young, 2010). This would align with studies on cognitive demand that have found more mind-wandering on longer or more difficult tasks (Feng, D'Mello, & Graesser, 2013; Mason et al., 2007; Seli, Risko, Smilek, & Schacter, 2016). Interestingly, despite increased self-reports of mind-wandering at longer ISIs, no-go accuracy is typically higher. Accordingly, a lower WMC relationship is another potential outcome at longer ISIs. While a weaker WMC relationship would not follow from the increase in the subjective measure of mind-wandering self-reports, the result would follow from the increase in the objective measure of accuracy. In such a case, mind-wandering may be only perceived to increase, or other factors also related to WMC could be influencing the relationship more than increased mind-wandering. Given the potential influence of ISI on go/no-go performance and its possible role in affecting individuals with varying levels WMC, the present study manipulated ISI within the context of perceptual and semantic go/no-go tasks.

5.1. Method

5.1.1. Participants

Participants in E2 came from the same subject pool as E1. However, none of the participants from E1 participated in E2. Of the 120 total participants who completed the perceptual versions of the tasks, 3 were unusable due to poor go trial accuracy, 2 were unusable due to poor no-go trial accuracy, and 1 exceeded the error total limits on the span tasks as described in E1, in accordance with the cut-offs described in E1. Of the 114 total participants who completed the semantic versions of the tasks, 9 were unusable due to poor go trial accuracy, 12 were unusable due to poor no-go trial accuracy, and 1 exceeded the error total limits on the span tasks, in accordance with the cut-offs described in E1. These exclusions resulted in a final sample of 114 participants in the Perceptual group and 92 participants in the Semantic group.

5.1.2. Tasks

Operation span. This task was the same as in E1.

Symmetry span. This task was the same as in E1.

Go/no-go – perceptual. This task was similar to the perceptual digits task in E1b. The short ISI version was identical. However, the long ISI version included a blank 2000 ms screen between the end of the mask and the start of the next trial. Including the mask, this rendered the short ISI 900 ms and the long ISI 2900 ms. See Fig. 1 for the task structure.

Go/no-go – semantic. This task was similar to the semantic task in E1a. The short ISI version was identical. However, the long ISI version included a blank 2000 ms screen between the end of the mask and the start of the next trial. Including the mask, this rendered the short ISI 900 ms and the long ISI 2900 ms.

5.1.3. Procedure

The procedure for E2 was very similar to E1 with the order of the two ISI versions of the go/no-go task being counterbalanced across subjects. Half of participants completed the perceptual versions of the tasks and the other half of participants completed the semantic versions of the tasks. Half of each of these groups completed the appropriate short ISI version first followed by the long ISI version and the other half of each group completed the long ISI version before the short ISI version. As in E1, participants completed the two WMC measures before completing the go/no-go tasks.

5.1.4. Analyses

Analyses for E2 are largely similar to those in E1. However, task (perceptual/semantic) was a between-subjects variable and ISI (900 ms/2900 ms) was a within-subjects variable.

5.2. Results

Of the final 114 participants in the perceptual task group for E2, 58 participants completed the short ISI task first, and the other 56 completed the long ISI task first. Of the final 92 participants in the semantic task group, 48 participants completed the short ISI task first, and the other 44 completed the long ISI task first. Descriptive statistics for these subgroups are presented in Table 8.

5.2.1. WMC measurement

Performance on span tasks was consistent with the normed samples (Redick et al., 2012) for both the perceptual and the semantic groups (Table 8). The two are correlated (perceptual: $r = 0.26$, $p = .01$; semantic: $r = 0.48$, $p < .001$), justifying the composite scores used in all further analyses.

5.2.2. Sensitivity and bias

The d' measure was significantly larger in the perceptual task than in the semantic task, as shown in Table 9. There was also a main effect of ISI such that the short ISI lead to smaller d' than the long ISI. This pattern held within both perceptual and semantic tasks when analyzed separately (Fig. 5A). In the combined analysis, ISI interacted with task, indicating the difference between the d' for short and long ISI tasks was larger in the perceptual version than in the semantic version. There was no main effect of order for the combined or separated analyses, but there was an ISI by order interaction in the combined analysis and the analysis of the perceptual group, but the ISI by order interaction was not significant in the semantic group.

Additionally, there was a main effect of WMC in the combined analysis for d' and the separate semantic analysis, due to a significant short ISI semantic task correlation with d' ($r = 0.21$, $p = .04$), though the long ISI semantic correlation was not significant ($r = 0.19$, $p = .08$). This main effect was not present in the separate perceptual analysis, likely due to non-significant correlations near zero.

Table 8
E2 descriptive statistics.

	E2 - Perceptual		E2 – Semantic	
	Short ISI	Long ISI	Short ISI	Long ISI
Ospan	59.93		58.29	
M (SD)	(9.68)		(11.03)	
Sspan	30.36		31.42	
M (SD)	(6.84)		(6.55)	
d′	2.56	3.34	2.21	2.73
M (SD)	(0.77)	(0.86)	(0.73)	(0.75)
C	−1.11	−0.80	−1.16	−0.81
M (SD)	(0.29)	(0.33)	(0.30)	(0.28)
Go Mean RT *M* (SD)	369	452	515	607
	(74)	(90)	(83)	(73)
Go RT ISD	109	108	140	129
M (SD)	(39)	(34)	(37)	(22)

Note: Ospan = Operation span, Sspan = Symmetry span, RT = response time, ISD = individual standard deviation, WMC = working memory capacity.

Table 9
ANCOVA Output – *d′* E2.

	E2 – Combined			E2 - Perceptual			E2 - Semantic		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Main Effects									
ISI	148.21	< 0.001	0.42	111.88	< 0.001	0.50	46.71	< 0.001	0.34
WMC	5.94	0.016	0.03	1.81	0.181	0.07	5.07	0.027	0.05
Order	0.42	0.519	0.00	0.04	0.845	0.00	1.23	0.271	0.01
Task	27.05	< 0.001	0.12	–	–	–	–	–	–
2-Way Interactions									
ISI × WMC	0.49	0.486	0.00	1.15	0.287	0.01	0.04	0.852	0.00
ISI × Order	9.74	0.002	0.05	6.98	0.009	0.06	3.18	0.078	0.04
ISI × Task	5.53	0.020	0.03	–	–	–	–	–	–
Order × Task	0.82	0.366	0.00	–	–	–	–	–	–
3-Way Interactions									
ISI × Task × Order	0.28	0.599	0.00	–	–	–	–	–	–

Note: ISI = Long vs. Short, Order = Long or short first, Task = Perceptual vs. Semantic. WMC is a continuous variable used as a covariate in these analyses.

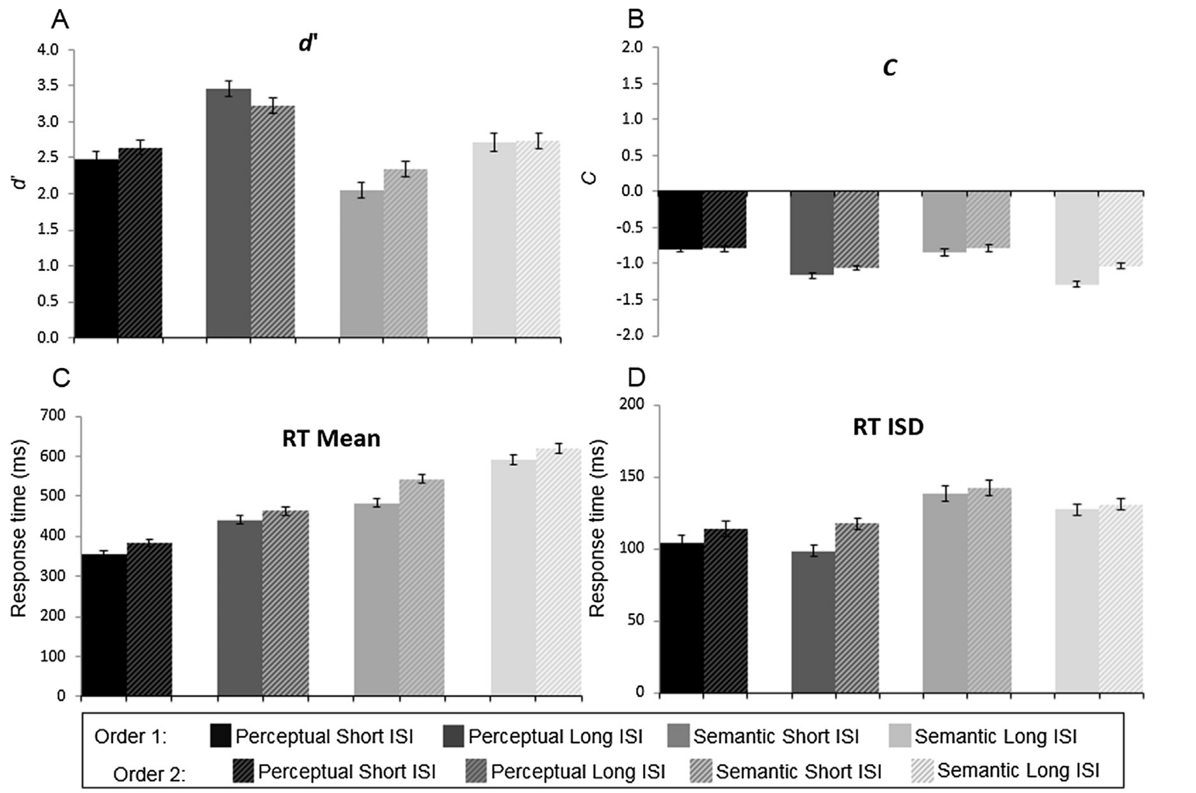

Fig. 5. Results from E2. (A) *d′*, (B) *C*, (C) mean RT, and (D) RT ISD; ISI = Inter-stimulus interval; error bars are ± 1 standard error of the mean. For order, 1 = Long ISI task first, 2 = Short ISI task first.

For *C*, there was a main effect of task such that there was a stronger go bias in the short ISI tasks versus the long ISI tasks in the combined sample and the separated perceptual and semantic analyses (Fig. 5B). There is also a main effect of order in the combined sample and the semantic analysis, but not in the perceptual analysis, such that there was a stronger go-bias when the long ISI task was completed first. Similarly, an ISI by order interaction occurs in the combined and the semantic only analyses, but not in the perceptual analyses, such that when the long ISI task is first, there is a particularly strong go bias in the short ISI task that follows (see Table 10).

5.2.3. Response times

A main effect of task, as seen in Table 11, indicated that mean RTs in the perceptual task were faster than those in the semantic

Table 10
ANCOVA Output – *C* E2.

	E2 – Combined			E2 – Perceptual			E2 - Semantic		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Main Effects									
ISI	203.93	< 0.001	0.50	92.74	< 0.001	0.46	116.20	< 0.001	0.57
WMC	0.26	0.611	0.00	0.05	0.823	0.00	1.00	0.320	0.01
Order	9.71	0.002	0.05	1.38	0.242	0.01	10.46	0.002	0.01
Task	0.84	0.362	0.00	–	–	–	–	–	–
2-Way Interactions									
ISI × WMC	0.41	0.522	0.00	0.14	0.706	0.00	0.29	0.589	0.00
ISI × Order	9.56	0.002	0.05	2.23	0.138	0.02	8.60	0.004	0.09
ISI × Task	0.54	0.463	0.00	–	–	–	–	–	–
Order × Task	2.12	0.147	0.01	–	–	–	–	–	–
3-Way Interactions									
ISI × Task × Order	0.98	0.323	0.01	–	–	–	–	–	–

Note: ISI = Long vs. Short, Order = Long or short first, Task = Perceptual vs. Semantic. WMC is a continuous variable used as a covariate in these analyses.

Table 11
ANCOVA Output – Mean RTs E2.

	E2 – Combined			E2 - Perceptual			E2 - Semantic		
	F	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Main Effects									
ISI	325.21	< 0.001	0.62	156.97	< 0.001	0.59	170.21	< 0.001	0.66
WMC	0.06	0.815	0.00	0.74	0.392	0.01	0.39	0.533	0.00
Order	12.68	< 0.001	0.06	3.36	0.062	0.03	9.98	0.002	0.10
Task	224.96	< 0.001	0.53	–	–	–	–	–	–
2-Way Interactions									
ISI × WMC	0.00	0.993	0.00	0.15	0.700	0.00	0.25	0.619	0.00
ISI × Order	3.86	0.051	0.02	0.24	0.625	0.00	4.91	0.029	0.05
ISI × Task	0.93	0.335	0.01	–	–	–	–	–	–
Order × Task	0.83	0.364	0.00	–	–	–	–	–	–
3-Way Interactions									
ISI × Task × Order	1.65	0.200	0.01	–	–	–	–	–	–

Note: ISI = Long vs. Short, Order = Long or short first, Task = Perceptual vs. Semantic. WMC is a continuous variable used as a covariate in these analyses.

task. The main effect of ISI indicated the short ISI resulted in faster mean RTs than the long ISI. There was a main effect of order for mean RTs such that mean RTs were shorter overall when the long ISI task was first. There were no interactions for mean RTs (Fig. 5C). In regard to WMC, there was no main effect and no interactions. This lack of effect follows from non-significant correlations all near zero between WMC and mean RTs across the tasks and ISIs.

For RT ISDs, as shown in Table 12, there was a main effect of task with the semantic RT ISDs being more variable than the perceptual RT ISDs. There was also a main effect of ISI with the short ISI leading to more variable ISDs than the long ISI. Importantly, there was an interaction between ISI and task, with the difference in RT ISDs between long and short ISI being present only in the semantic task (Fig. 5D). There was a main effect of order for RT ISDs, but no interactions involving order. Additionally, there was no main effect for WMC in the combined analysis and in the semantic analysis. Though all the correlations involving RT ISDs were negatively related to WMC (Table 13), only the long-ISI semantic RT ISDs reached significance ($r = -0.21$, $p = .047$). Additionally, there were no interactions with WMC.

5.3. Discussion

E2 investigated the effects of manipulating ISI, which resulted in main effects of ISI on all outcome measures. The short ISI produced faster mean RTs on go trials, lower *d′* values, and stronger (more negative) *C*. There were also order interactions with ISI such that performance on the short ISI task was affected by the long ISI task when the short ISI task came second. This effect was present for both *d′* and *C* but not present for mean RTs. Specifically, *d′* and *C* are both lower in the short ISI task when the short ISI task is second.

E2 was specifically intended to test whether the manipulation of ISI would induce a difference in the relationships between WMC and the go/no-go outcomes. Such a difference would indicate that ISI was having an effect on the way in which the task performance

Table 12
ANCOVA Output – RT ISDs E2.

	E2 – Combined			E2 - Perceptual			E2 - Semantic		
	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
Main Effects									
ISI	7.07	0.008	0.03	0.12	0.731	0.00	9.82	0.002	0.10
WMC	3.30	0.071	0.02	0.88	0.351	0.01	3.00	0.087	0.03
Order	5.00	0.027	0.02	5.66	0.019	0.05	0.61	0.437	0.01
Task	40.68	< 0.001	0.17	–	–	–	–	–	–
2-Way Interactions									
ISI × WMC	0.00	0.948	0.00	0.03	0.867	0.00	0.00	0.953	0.00
ISI × Order	1.06	0.304	0.01	2.58	0.111	0.02	0.00	0.996	0.00
ISI × Task	4.91	0.028	0.02	–	–	–	–	–	–
Order × Task	1.52	0.219	0.01	–	–	–	–	–	–
3-Way Interactions									
ISI × Task × Order	1.09	0.299	0.01	–	–	–	–	–	–

Note: ISI = Long vs. Short, Order = Long or short first, Task = Perceptual vs. Semantic. WMC is a continuous variable used as a covariate in these analyses.

Table 13
Correlations with WMC E2.

	Perceptual		Semantic	
	Short ISI	Long ISI	Short ISI	Long ISI
N =	114		92	
Correlations				
d'	0.06	0.16	0.21*	0.19
C	−0.05	0.00	0.06	0.12
Mean RT	−0.11	−0.06	0.09	0.04
RT ISD	−0.09	−0.09	−0.12	−0.21*
Reliabilities				
Mean RT	0.76	0.95	0.73	0.88
RT ISD	0.72	0.90	0.72	0.80

Note: * indicates $p < .05$, reliabilities given for split half RT measures (Spearman-Brown), the d' and C measures are calculated from summary variables and do not lend themselves to reliability estimates.

was dependent upon underlying constructs such as attention and inhibition that are strongly correlated with WMC. In turn, changes due to ISI would help to explain some of the inconsistencies in the literature regarding the relationships between go/no-go performance and WMC.

Specifically, if the use of short versus long ISIs produced the mixed relationships with WMC in the perceptual task version literature, introducing the long ISI into the semantic task version should have resulted in more varied relationships with WMC in the semantic task. This pattern does seem to appear in the present study. Table 14 shows the correlations between WMC and given

Table 14
Correlations with WMC Comparison from E1 to E2.

	Perceptual			Semantic		
	E1b	E2 - Short	E2 - Long	E1a	E2 - Short	E2 - Long
N =	49	58	56	53	48	44
Correlations						
d'	0.35*	0.28*	0.00	0.33*	0.42*	−0.02
C	0.13	0.14	−0.08	0.33*	−0.06	0.14
Mean RT	0.17	0.07	−0.13	0.28*	−0.02	0.08
RT ISD	−0.03	0.02	−0.01	−0.31*	−0.40*	−0.14
Reliabilities						
Mean RT	0.81	0.76	0.95	0.88	0.70	0.89
RT ISD	0.83	0.66	0.85	0.68	0.78	0.81

Note: * indicates $p < .05$, reliabilities given for split half RT measures (Spearman-Brown), the d' and C measures are calculated from summary variables and do not lend themselves to reliability estimates.

outcome measures for short and long ISI conditions from E2 and the short ISI comparison from E1, which is identical to the short ISI task in E2. Importantly, the E2 correlations in Table 14 are only from those participants who completed the given task as their first go/no-go task, which was necessary due to the order effects found in E2. The correlations from E2 with short ISI are mostly consistent with the correlations from the matching E1 short ISI comparison. In contrast, the long ISI task outcomes are uncorrelated for both the perceptual and semantic task versions in E2, sometimes even drifting into the opposite direction compared to the short ISI correlations. This pattern of results is clear in the *d′* and RT ISD measures. Importantly, it is the relationships with accuracy measures that normally show such variability in the literature whereas relationships with mean RTs tend to be more consistently absent across tasks.

From the ANCOVAs, WMC is a significant covariate for *d′* but not for RT ISDs or *C*, and does not interact with ISI for any of the variables. Most interestingly, whereas WMC was significant as a covariate in the overall analyses and the semantic analysis for *d′*, it was not a significant covariate in the separated perceptual task analyses for any of the outcomes. This echoes the lack of relationships between WMC and perceptual tasks seen elsewhere in the literature as well as non-significant main effects for WMC in E1b, which only included perceptual tasks, for mean RT and RT ISD. WMC was correlated with *d′*, and RT ISD for short ISI tasks in similar patterns to the relationships found in E1. However, these relationships did not appear in the long ISI tasks.

Additionally, in the ANCOVAs, the order variable had a significant interaction with ISI for one outcome measures. Specifically, in mean RTs, when the short ISI task was first, mean RTs on the short ISI task were slower than when the short ISI task was second. Conversely, when the long ISI task was first, mean RTs were faster than when the long ISI task was second. These order effects, while complicating the picture, are not inconsistent with the idea that ISI could cause variability in the relationship with WMC. If the relationship with WMC is stronger in the first task completed, and related constructs like attention and inhibition are being used more, several accounts would propose effects on subsequent tasks.

Overall, the patterns found in E2 suggest ISI plays a role in the strength and consistency of relationships between outcome measures and WMC. However, there seem to be additional differences in these relationships based specifically on task type – perceptual versus semantic. This pattern shows smaller or lacking relationships with perceptual tasks versus semantic tasks, unlike E1 but consistent with some of the literature.

6. General discussion

This project provides evidence for the ways in which task manipulations affect the relationships with underlying processes that a task is supposed to be measuring. If the manipulations do not have effects, or have consistent effects, on performance outcomes, then the corresponding connections to underlying processes would be unaffected or affected in a consistent manner. However, should task performance vary in an unpredictable manner depending on different manipulations, the corresponding relationships to underlying processes may also be equally unpredictable or inconsistent.

In the present studies, there are two major findings. First, perceptual versus semantic task performance is consistently different across many task manipulations with perceptual tasks, typically resulting in faster and more accurate performance. However, while performance is different, the relationships between outcome measures and WMC are consistent between perceptual tasks and identically structured semantic tasks. Second, as proposed, ISI had an effect on the relationship between WMC and various outcome measures. Importantly, this effect of ISI did not completely explain the differences seen in perceptual versus semantic tasks. So, while ISI does have an effect on the relationships, it must not be the only contributing factor.

These findings do include some limitations. Ideally, in E2, both the ISI critical manipulation and the important task type manipulation would have been within-subjects. However, the time spent doing go/no-go tasks would have so far exceeded the time spent in E1 and been practically incomparable. Therefore, the more important ISI manipulation was chosen as the within-subjects manipulation with task type remaining between-subjects. Importantly, E1 thoroughly investigates the contributions of task type and order of tasks both with similar stimuli and different stimuli such that the necessity of retaining task type in E2 as a between-subjects variable becomes minimal.

The comparisons of task type (perceptual vs. semantic) in E1a-c produced differences in accuracy and RT outcomes, but it is possible that we could have increased the difficulty of the perceptual decision (or decreased the difficulty of the semantic decision) and produced more similar performance levels. An interesting follow-up study could systematically manipulate the difficulty of the perceptual and semantic tasks to investigate how this affects go/no-go performance. Across E1a-c, the various versions of perceptual go/no-go tasks used produced similar levels of performance. The similarity of WMC relationships with perceptual and semantic go/no-go performance in E1 suggests that regardless of whether the task type or task difficulty was the critical comparison in E1, that factor is not the critical factor causing differences in the literature. Clarification of the task type versus task difficulty factor could, however, be important when asking other questions about the use of this task (for similar discussion with auditory vs. visual SART, see Seli et al., 2012).

Another limitation occurs within the use of *d′* as a tool to evaluate accuracy in terms of both hit rates and false alarm rates. While the advantage of *d′* is that it combines go and no-go performance into one metric, and it is used widely in the go/no-go literature, it is important to note the risk associated with using this measure in a task with imbalanced go and no-go trial frequencies, which the measure was not developed to handle (Thomson, Besner, & Smilek, 2016). Specifically, when the frequencies are severely imbalanced, as in the standard go/no-go, the relative contributions of the hits and false alarms are also severely disproportionate. This imbalance can cause misleading *d′* values as a small change in hit rate will have a much larger effect on *d′* than an equal change in false alarms. A more theoretical issue is proposed by Thomson et al. regarding the interpretability of *d′* in tasks like the go/no-go because the measure may be influenced by moving response criteria as opposed to the hypothesized change in sensitivity. However, this issue is mostly pertinent for studies measuring *d′* changes with time-on-task. Though changes in *d′* are not of interest in the present study, *d′* still must be interpreted cautiously.

One interesting possibility arises from the consistent use of the same WMC tasks across the studies in the present work. While nearly all the studies cited in Table 1 used similar complex span tasks to measure WMC, the studies using perceptual versions of go/no-go tended to use one WMC task where the studies using semantic versions of go/no-go tended to use multiple WMC tasks and use composite scores. In the current studies, a composite score is calculated from two WMC tasks. The previous semantic version studies and the present work, using composite score measures for WMC, find the more consistent relationships with WMC. It is possible that our recommendation of using multiple tasks to measure a construct is affecting the study in a different way than expected. Rather than the go/no-go manipulations altering the relationships (which we do not replicate in the present studies), it could be that the differential use of WMC tasks is the cause of the inconsistencies noted in the literature. A follow-up study manipulating WMC measures while controlling go/no-go would be required to decisively point to this conclusion. Either way, this pattern also bolsters the importance of the message that the use of multiple tasks are better for the measurement of underlying constructs.

Future studies may want to consider the implications of the present work for other types of tasks and their relationships with the underlying constructs they are meant to measure. The importance of this investigation is not limited to whether WMC relationships with go/no-go tasks do or do not align with our expectations, but rather extends to the connections between all tasks attempting to measure cognition and the cognitive control constructs such tasks attempt to measure. More importantly the present work illustrates that certain manipulations may be influencing these relationships in impactful and unanticipated ways. Though an important finding, it is not the first instance of such disruptions. Kane and Engle (2003) found that though individual differences in WMC were related to Stroop performance, as would be expected based on executive-attention theory (Engle & Kane, 2004), manipulations such as proportion congruency, presence of feedback, and order of tasks affected this relationship similarly to the effects found in the present work. Additionally, comparing across studies, whereas Kane and Engle used a vocal response and did not find relationships with WMC in RTs, Unsworth and Spillers (2010) used a button press response in a similar Stroop task and found relationships with WMC and RTs, suggesting response type is another manipulation that affects these relationships.

An additional similarity between the present work and Kane and Engle (2003) is the inconsistency with where the WMC relationships become evident. Kane and Engle (2003) found WMC relationships with the Stroop task primarily in the accuracy measures but not in the RTs. Similarly, in the present work and much of the go/no-go literature, mean RTs from the perceptual go/no-go tasks were unrelated to WMC. RT ISDs, particularly in perceptual versions, were generally inconsistent in their relationships with WMC. This speaks to a wider problem of inconsistency in the literature with WMC relationships and the efforts to determine why relationships are found in some instances and not others and more specifically found in some variables sometimes and other variables other times.

7. Conclusion

Given the reliance on single tasks throughout the literature, this work has implications for the way in which assessments and studies are designed and carried out for both clinical and research purposes. While the perceptual tasks are advantageous due to the lack of reliance on vocabulary knowledge to make semantic decisions, the semantic tasks are advantageous in that the relationships with working memory are more consistent and are therefore likely getting at the attention and inhibition constructs more clearly. However, extending the ISI was enough to mitigate this advantage and render the tasks equally variable in their relationships with WMC. To conclude, it is advisable to use more than one assessment when attempting to measure a construct and the assessments should be chosen carefully with the effects of various task manipulations in mind.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2019.03.006.

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