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OBSERVATION

Time Limits During Visual Foraging Reveal Flexible Working Memory Templates

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During difficult foraging tasks, humans rarely switch between target categories, but switch frequently during easier foraging. Does this reflect fundamental limits on visual working memory (VWM) capacity or simply strategic choice due to effort? Our participants performed time-limited or unlimited foraging tasks where they tapped stimuli from 2 target categories while avoiding items from 2 distractor categories. These time limits should have no effect if capacity imposes limits on VWM representations but more flexible VWM could allow observers to use VWM according to task demands in each case. We found that with time limits, participants switched more frequently and switch-costs became much smaller than during unlimited foraging. Observers can therefore switch between complex (conjunction) target categories when needed. We propose that while maintaining many complex templates in working memory is effortful and observers avoid this, they can do so if this fits task demands, showing the flexibility of working memory representations used for visual exploration. This is in contrast with recent proposals, and we discuss the implications of these findings for theoretical accounts of working memory.

Public Significance Statement

When we search for 2 things at once, are 2 search templates simultaneously activated, or do we switch rapidly between the 2 templates, in essence only searching for 1 item at any given moment? Our results suggest that while we may avoid keeping 2 search templates active in visual working memory due to the effort involved, we are able to do so when the task demands require this or reward it for a short period of time. The fact that participants seem to be able to change their foraging patterns according to task demands suggests that visual working representations used for attentional guidance are flexible, but not fixed at 1 feature as some current theories suggest. This finding has important consequences for theoretical conceptions of visual working memory.

Keywords: foraging, attention, visual working memory, visual search, working memory template

As we interact with our visual environment, there are typically many behaviorally relevant sources of information at any given time. Tasks involving search for multiple targets of more than one type may capture this scenario experimentally. Until recently, the most common paradigm for investigating search-like behavior has involved the detection of single targets among multiple distractors (Cavanagh & Chase, 1971; Green & Anderson, 1956; Kristjánsson, 2015; Treisman & Gelade, 1980; Wolfe, 1998). While this classic visual search paradigm has yielded important insights, a number of groups have begun to explore so-called *foraging* tasks involving multiple targets among multiple distractors (e.g., Cain, Vul, Clark, & Mitroff, 2012; Gilchrist, North, & Hood, 2001; Hills, Kalff, & Wiener, 2013; Kristjánsson, Jóhannesson, & Thornton, 2014; Wolfe, 2013; Thornton & Horowitz, 2004). This approach, which takes inspiration from a long history of animal studies (e.g., Bond, 1983; Dawkins, 1971; Langley, Riley, Bond, & Goel, 1996; Reid & Shettleworth, 1992), may better capture interactions with dynamic visual environments.

What mechanisms enable us to efficiently select targets, while simultaneously inhibiting distractor selection? Templates that reflect task demands are typically assumed to guide attentional selection during search and foraging and are commonly thought to be stored in visual working memory (VWM) until they are no

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longer task relevant (Awh & Jonides, 2001; Bundesen, 1990; Desimone & Duncan, 1995; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Soto, Hodsoll, Rotshtein, & Humphreys, 2008; Vickery, King, & Jiang, 2005). According to many conceptions, this guidance is severely limited because of the low capacity of VWM and at the extreme, only one feature value (Oberauer, 2002; Olivers et al., 2011; van Moorselaar, Theeuwes, & Olivers, 2014; see also Huang & Pashler, 2007) or less conservatively, one feature value per dimension (e.g., Moore & Osman, 1993; Wolfe, 2007) can be maintained in VWM at any given time. For example, van Moorselaar et al. (2014) found that attentional capture by memory-related distractors was stronger when VWM was loaded with a single item than when memory was loaded with more than a single item. Based on this, they argued for a division within VWM between a single active template that determines selection and accessory representations that do not.

But other evidence contradicts this, suggesting that although VWM capacity is limited, it is more flexible than these accounts imply. Beck, Hollingworth, and Luck (2012) found that when searching for a target that could be of two different colors, observers switched between stimuli of the two colors at little cost. They argued that observers activate two templates simultaneously or sequentially based on task instructions and that the templates guiding search can be used flexibly. Other researchers have reached similar conclusions as Beck et al. (2012), that two or more templates can be simultaneously active in visual working memory (e.g., Carlisle, Arita, Pardo, & Woodman, 2011). Kristjánsson et al. (2014) introduced a foraging task on iPads where observers had to tap 40 targets (e.g., red and green disks) among 40 distractors (e.g., blue and yellow disks) on each trial. Observers typically switched frequently and rapidly between target types during such feature-based foraging. This finding is also at odds with the proposal that only one feature value in VWM can guide attention at a given moment. If this were the case, we would not expect observers to be able to switch so readily, for the simple reason that it takes time to load items into an active VWM state, since there is a well-documented cost to switching templates (Found & Muller, 1996; Houtkamp & Roelfsema, 2009; Olivers & Humphreys, 2003). This cost may be up to 250 ms per switch (Dombrowe, Donk, & Olivers, 2011; see also Vickery et al., 2005). Although Vogel, Woodman, and Luck (2006) reported that loading VWM may occur as quickly as 50 ms, the situation during foraging probably differs, as lingering activity from the preceding target must be "flushed out," as intrusions from previous targets would otherwise interfere with selection, if working memory has room for only one active template (see, e.g., Dombrowe et al., 2011; Kristjánsson & Driver, 2008).

Kristjánsson et al. (2014) also found that during more complicated foraging where targets were distinguished from distractors by both color and shape (a "conjunction" manipulation; Treisman, 1977), foraging strategies changed quite dramatically. Specifically, most observers now selected targets in long "runs" of the same type, often selecting all targets from one category before switching to the next. Such runs are more consistent with the single-template proposal, but note that the same observers showed two vastly different selection modes during feature and conjunction foraging; short runs with frequent, close to random switches between target categories during feature foraging; and long runs with infrequent, nonrandom switches between target categories during conjunction foraging.

Here we ask whether switching patterns during difficult foraging reflect strategy or actual inability to maintain more than one template. For example, might it be optimal not to switch during the more difficult tasks? Or does working memory only allow observers to maintain one active template at a time (Oberauer, 2002; Olivers et al., 2011)? Another possibility is that observers select targets in runs, since maintaining complex templates, or a large number of templates, is effortful, yet still possible.

In the work of Kristjánsson et al. (2014), participants had unlimited foraging time (see also Jóhannesson, Thornton, Smith, Chetverikov, & Kristjánsson, 2016; Ólafsdóttir, Kristjánsson, Gestsdóttir, Jóhannesson, & Kristjánsson, 2016). Here we wondered whether observers could be encouraged to switch more frequently. An interesting perspective comes from a recent study where four objects moved down the screen in rows, reminiscent of the classic *Space Invaders* video game (Thornton, Jóhannesson, & Kristjánsson, 2015). Each row contained two targets and two distractors. Participants moved a player icon via the tilt control feature of an iPad to collide with either target. For both feature and conjunction targets, observers predominantly chose the closest targets rather than the same target, showing that they could switch when it was more practical. Observers may therefore be able to load working memory up to the required degree (Alvarez & Cavanagh, 2004; Bays & Husain, 2008). But if maintaining conjunctions in working memory is effortful, observers may choose not to do so and focus on a single item or feature value.

If observers can switch between target types during conjunction foraging, runs of same target selection may therefore reflect a strategy of convenience rather than internal constraints. Interestingly, in the work of Kristjánsson et al. (2014) and Jóhannesson et al. (2016), a subgroup (~15%–20%) of observers switched easily between target types during conjunction foraging instead of using long runs of target selection (termed *super foragers*). Their performance patterns raised speculation over whether they had better working memory or attentional inhibition abilities than others. Jóhannesson, Kristjánsson, and Thornton (2017) found no evidence for superior abilities, however, which may indicate that these observers simply use a different strategy during foraging than the majority.

We therefore asked whether imposing time limits on foraging would induce a strategy change, or whether previously seen differences between run patterns in feature and conjunction conditions reflect a fixed limit. With time constraints, the task involves collecting as many targets as possible, rather than finishing all targets. Since choosing targets in runs entails that observers must cover longer distances during foraging, time limits might induce a strategy of choosing closer items, and therefore increase switch rates. We asked observers to forage for as many targets as they could, comparing this with foraging when they had unlimited time.

Method

Participants

Seventeen students at the University of Iceland (16 female), 21–31 years old ($M = 24.1$) participated, receiving course credit for participation. Twenty students were booked for participation, with the goal of having at least 16 participants. Students who did not show up were not replaced. All participants had normal or corrected-to-normal vision. Prior to data collection, all participants gave written informed consent and all aspects of the study were reviewed and approved by the local ethics committee.

Equipment

The stimuli were displayed on an iPad 2 with screen dimensions of 20 × 15 cm and an effective resolution of 1024 × 768 pixels. The iPad was placed on a table in front of participants in landscape mode, so that viewing distance was approximately 60 cm. Stimulus presentation and response collection were carried out with a custom iPad application written in Swift using Xcode.

Stimuli

During feature-based foraging, the targets were red and green disks while the distractors were yellow and blue disks for half the participants. For the other half, this was reversed (see Figure 1). During conjunction foraging, the targets were red squares and green disks and the distractors were green squares and red disks for half the participants but reversed for the other half. There were 80 stimuli on the screen at the start of each trial, 20 stimuli of each type, 40 targets and 40 distractors. Their diameter was 20 pixels, approximately 0.37°. The items were randomly distributed across a nonvisible 10 × 8 grid that was offset from the screen edge by 150 × 100 pixels. The whole viewing area therefore occupied 15 × 12 cm (approximately 14.3° × 11.4°). The exact position of individual items within the grid was jittered by adding a random horizontal and vertical offset to create less uniform appearance. Gaps between rows and columns ensured that items never approached or occluded one another. The overall spatial layout and location of targets and distractors was generated independently on every trial.

Procedure

The experiment was run in a small quiet room with normal lighting. On each trial, participants were instructed to tap all targets as quickly as possible using the index finger of their dominant hand. A counter at the bottom of the screen indicated the number of completed trials. Participants were instructed to finish 20 trials and let the experimenter know when they had finished. They started with two practice trials, to familiarize themselves with the iPad and the stimuli and to get a feel for how sensitive the touch screen was to the tapping. They were told that they would complete eight blocks of 20 trials for each condition and that they could take a break between any of the blocks. One completed trial refers to when either the time limit (5, 10, or 15 s) was reached or,

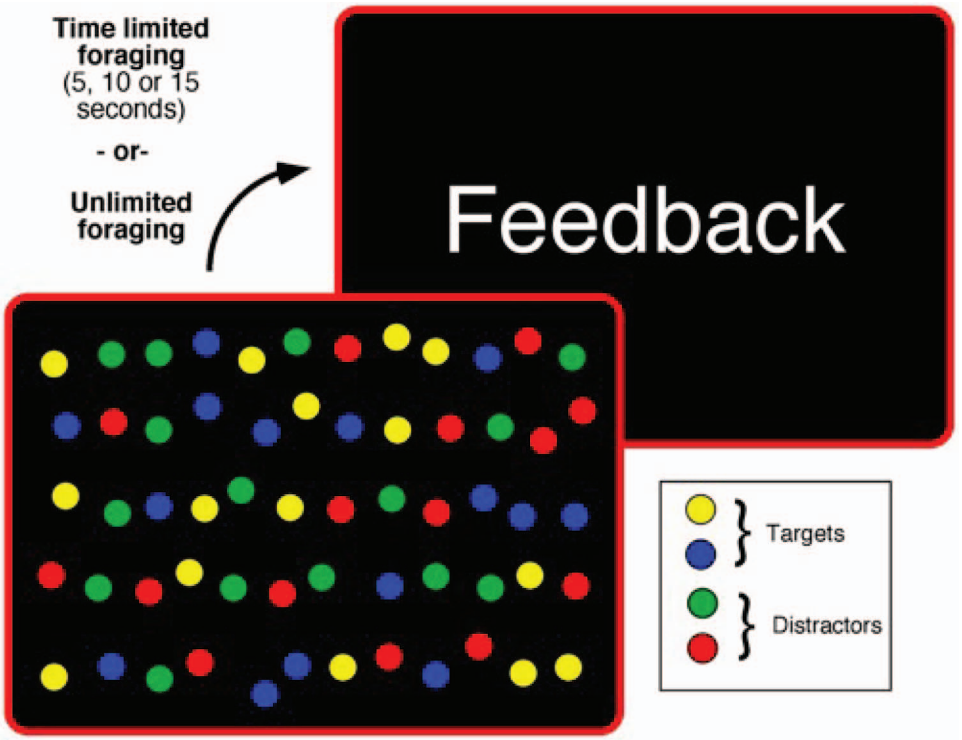

Figure 1. The experimental paradigm. The foraging displays contained 40 targets, in this case the blue and yellow dots (the darkest and lightest shades of grey) among green and red dot (the other two shades of grey) distractors (feature foraging). During conjunction foraging, the targets were distinguished from distractors on two features, color and shape, so the targets were red squares and green disks among red disks and green squares, or vice versa. Participants had 5, 10, or 15 ms to collect as many targets as they could by tapping them, and they also foraged under a condition in which they had as much time as they wanted ("unlimited" condition). See the online article for the color version of this figure.

in the case of the no time-limit condition, all 40 targets were tapped. Participants started each experimental block by pressing a "play" button on the screen when ready and the stimuli appeared. Targets disappeared immediately after they were tapped. If participants tapped a distractor, the trial ended, an error message was given, and they could start a new trial by pressing the play button. When all targets had been tapped, or the time limit was up, a smiley face appeared along with feedback about the number of targets tapped (or the time it took to tap all 40 targets). The order of the conditions was counterbalanced across participants so that half of the participants started with feature foraging and half with conjunction foraging, half of the participants started with the shortest time limit working upward toward the no time limit condition, while this was reversed for the other half. The counterbalancing scheme was created for 20 participants. As explained in the participant section, only 17 showed up so that three condition orders were not used.

Data Analysis

The data were cleaned by erasing taps that were not on any stimuli (10,456 taps, ~10% of total taps). Then any trial that ended with an error (see error rates in Table 1) was deleted (374 trials). This left 2,720 trials in the final dataset. The independent variables in the analyses were condition (feature vs. conjunction foraging) and time limit (5, 10, and 15 s and a no-time limit condition). The dependent variables were the number of runs and intertarget times (ITTs). A run is defined as a sequence of repeated selections from the same target group, and directly reflects the number of switches between target categories. One switch translates to two runs, 10 switches mean 11 runs, and so forth

The ITT measures the duration between taps on two successive targets. One potential reason for the large differences in run behavior during foraging seen in previous studies is that switching between target types entails a cost, in particular during difficult foraging tasks. Participants may therefore rarely switch during conjunction foraging to maximize speed. Switch costs can be assessed by measuring how ITTs differ by whether observers tap the same targets as they last did, or switch to the other target type. In the work of Jóhannesson et al. (2016) and Ólafsdóttir et al. (2016), switch-costs were much higher during conjunction than feature foraging during foraging with no time limits. Examining the pattern of ITTs, particularly with respect to switch costs, can therefore shed light on foraging strategies.

For the repeated-measures analyses of variance (ANOVAs), Greenhouse-Geisser corrections to the degrees of freedom were used to correct for any violations of sphericity. Data were missing for one participant in a single condition. Analyses for other conditions were run, with and without this participant. This did not affect the results and the participant was excluded from analyses. This means that 16 participants are included in all analyses. This meant, however, that there was not a balance among the four condition orders. Instead, the order is balanced for condition and time limit independently so that 8 participants started with feature foraging, and 8 participants started with the shortest time limits.

Results

Distributions of run number by foraging condition and time limit are shown in Figure 2. Overall, the number of runs during feature foraging is close to random, but the number of runs during conjunction foraging is highly skewed where participants seem to prefer completing each trial with as few switches as possible, as in our previous foraging studies (Jóhannesson et al., 2016, 2017; Kristjánsson et al., 2014; Ólafsdóttir et al., 2016).

However, closer examination reveals that during conjunction foraging, the introduction of time limits consistently influenced the run pattern. Specifically, the shorter the time limit the more likely participants were to switch between conjunction target categories. As this pattern is difficult to assess from Figure 2—since the longer time limits allow for more switches overall due to higher number of targets tapped and more time to switch—we normalized across time limits, as is described next.

Analyzing the number of runs by per second of foraging (Figure 3A) and by per item tapped (Figure 3B) evens out the differences between conditions, providing a clearer comparison between conditions. As Figure 3 shows, the number of switches actually increases as foraging time decreases, with the only exception being feature foraging, shown in Figure 3B. Note also that this increase in runs is not accompanied by an increase in error rates that are actually largest for the no time limit condition (see Table 1).[1]

To explore these patterns, we conducted a repeated-measures ANOVA on the number of runs (per participant) per second with condition (feature and conjunction) and time limit (5, 10, and 15 s) as factors. There was a significant main effect of condition, $F(1, 15) = 138.58$, $p < .001$, $\eta_p^2 = .90$, replicating the general reduction in runs during conjunction foraging seen in previous studies. Importantly, there was also a main effect of time limit, confirming the pattern seen in Figure 3 that people switch more often per second with shorter time limits, $F(1.58, 23.63) = 20.82$, $p < .001$,$\eta_p^2 = .58$. There was no Condition × Time Limit interaction, $F(1.79, 26.85) = 1.40$, $p = .264$, $\eta_p^2 = .09$. Post hoc analyses (pairwise comparisons with Bonferroni adjustment) revealed that the mean number of runs per second for each time limit differed significantly from the others (all *p*s $< .05$).

The same analysis was conducted for the mean number of runs per target. This also confirmed that there were significant main effects of condition, $F(1, 15) = 102.0$ $p < .001$, $\eta_p^2 = .87$, and time limit, $F(2.7, 39.8) = 5.4$, $p = .004$, $\eta_p^2 = .27$. There was also a significant interaction between condition and time limit, reflecting the fact that the number of runs per item remained almost constant through all time limits during feature foraging, but decreased for conjunction foraging, $F(2.2, 33.1) = 9.4$, $p < .001$, $\eta_p^2 = .39$. Post hoc analysis of the conjunction condition revealed that the 5-s time limit differed significantly from the 15-s time limit and the unlimited time condition.

A possible interpretation of these result is that the difference does not reflect the time limits per se, but rather that participants switch more at the start of each trial. To address this, we compared the switches for the first 5 s between all time-limit conditions; switches between seconds 5 and 10 for the 10-s condition, 15-s, and unlimited-time conditions; and switches between the 10th and the 15th second between the 15-s time limit and the unlimited-time limit condition. The results are shown in Figure 4.

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[1] Note that if observers made an error, they needed to perform an additional trial, so the error rates do not affect the other measures.

Table 1
Average Number of Tapped Targets, Error Rates, and Taps on Empty Areas by Time Limits for Feature and Conjunction Foraging

Time	Feature Targets	Feature Errors, %	Feature Mis-taps, %	Conjunction Targets	Conjunction Errors, %	Conjunction Mis-taps, %
5 s	14.82	3.68	13.30	13.28	11.23	11.20
10 s	28.93	3.13	13.10	24.85	14.79	9.70
15 s	38.65	8.99	10.90	35.08	20.37	8.70
Unlimited	40	8.99	11.70	40	22.20	8.10
Total	30.6	6.34	12.00	28.3	17.38	9.00

A repeated-measures 2 (condition) × 4 (time limits) ANOVA for the number of runs in the first 5 s of every trial showed significant effects of condition, time limit, and the interaction between them, $F(1, 15) = 147.14$, $p < .001$, $\eta_p^2 = .91$; $F(2.35, 35.19) = 6.23$, $p = .003$, $\eta_p^2 = .29$; $F(2.59, 38.88) = 6.98$, $p = .001$, $\eta_p^2 = .32$, respectively. Figure 4 reveals that the differences between time limits are larger during conjunction than feature foraging. We conducted separate repeated-measures ANOVAs for the two conditions with time limits as the independent variable. For feature foraging, the effect of time limits on the number of runs was not significant, $F(2.67, 39.99) = .173$, $p = .896$, $\eta_p^2 = .01$. For conjunction foraging the effect of time limits on the number of runs was, on the other hand, significant, $F(2.65, 39.82) = 13.53$, $p < .001$, $\eta_p^2 = .47$. This shows that participants do indeed switch more often the shorter the time limit, and not only during the first 5 s of each foraging trial. The results of ANOVAs for the 5- to 10-s period follow the same pattern: for feature foraging, $F(1.84, 27.52) = 2.37$, $p = .116$, $\eta_p^2 = .137$; and for conjunction foraging, $F(1.86, 27.86) = 7.59$, $p = .003$, $\eta_p^2 = .34$. For the last period measured, between the 10th and the 15th second, the repeated-measures ANOVAs were not significant: feature foraging, $F(1, 15) = .41$, $p = .53$, $\eta_p^2 = .03$; conjunction foraging, $F(1, 15) = .11$, $p = .75$, $\eta_p^2 = .01$.

Figure 5 shows the switch costs by condition. For conjunction foraging there is a large difference in switch costs between when foraging is time-limited and the no time limit conditions with much higher switch costs during unlimited foraging. A repeated-measures ANOVA on the ITTs where condition, time limit, and switch versus repeat were the factors and ITTs were the dependent variables, revealed that all factors significantly affected ITTs: condition, $F(1, 15) = 120.4$, $p < .001$; time-limit, $F(1.7, 25.0) = 178.4$, $p < .001$; switch, $F(1, 15) = 169.7$, $p < .001$. Each of the two-way and three-way interactions were also significant (all $ps < .001$).

The time limits decrease switch costs during feature and conjunction foraging, making switches faster than when there is no time limit. During conjunction foraging, there is a clear difference between the time limit and no time limit conditions (see Figure 5). In the no-limit condition, we see the same high switch costs, as in previous experiments. With time limits, the switch costs decrease dramatically, and are smallest for the shortest time limit. This result shows how switches are possible without much cost in speed or accuracy (see Table 1) even during "difficult" conjunction foraging. As we discuss further below, one contributing factor to this pattern may be that with time limits, participants are not required to find every item from a category. Elsewhere, we have found that ITTs appear particularly slow when participants begin to exhaust one of their two target categories (Ólafsdóttir et al., 2016; Kristjánsson, Thornton, & Kristjánsson, 2016).

Discussion

Templates stored in visual working memory (VWM) are generally thought to enable selection of task-relevant stimuli. While there is general agreement that VWM has limited capacity, the nature of VWM representations is hotly debated. According to some accounts, attentional guidance from working memory is limited to one feature value at any given moment (Oberauer, 2002; Olivers et al., 2011; van Moorselaar et al., 2014). The Boolean map theory of attention (Huang & Pashler, 2007) makes a similar

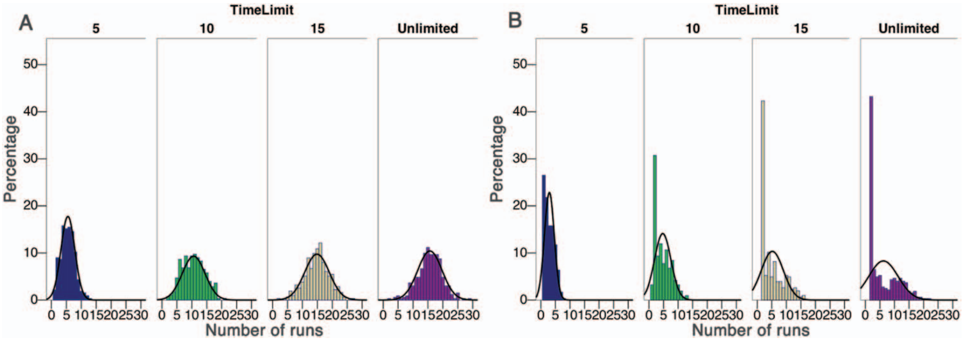

Figure 2. Number of runs (summed from all trials) with different time limits during (A) feature and (B) conjunction foraging. The percentage is the percentage of trials within each condition, so that the bars in each panel add up to 100%. The black lines in each curve shows a best-fitting Gaussian. See the online article for the color version of this figure.

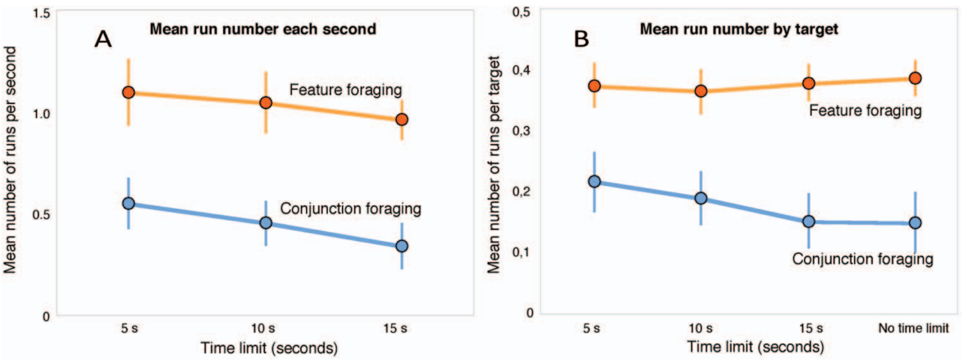

Figure 3. Mean number of runs, adjusted for (A) time and (B) number of targets tapped. The time adjustment is the number of runs divided by seconds for each time limit. The target adjustment is the number of runs divided by the number of targets tapped for each participant. The vertical lines through each point represent 95% confidence intervals. See the online article for the color version of this figure.

claim: that the visual input can be subdivided into to-be-attended and to-be-ignored regions on the basis of just one feature value. According to both these theories, only one control signal at a time can be sent from VWM to attentional mechanisms that implement visual selection. These conceptions therefore clearly predict that during foraging for many targets of two different types, observers would stick to the same target type (even during feature foraging) for long runs, to prevent effortful switching that would cause switch costs of around 200–250 ms.

We measured how easily observers can switch between target items during foraging for multiple targets of two different types. If VWM is limited to a single feature value, the best strategy would be to stick to one target type before switching to the other. This is a clear prediction from studies that show how costly switching between templates can be (Dombrowe et al., 2011; Found & Muller, 1996; Houtkamp & Roelfsema, 2009; Olivers & Humphreys, 2003). On the other hand, working memory may be applied in a more flexible manner, depending on the task in each case. Our findings can therefore cast light on theories of visual working memory. We found that when time limits were imposed on foraging, observers changed their strategy, switching more often between target types than when they had unlimited time to forage. This is an adaptive strategy, because when 40 targets are randomly distributed on a jittered grid of 80 items as is the case here, as participants tap the targets, the average distance between the remaining targets increases. If only one template is active while foraging for blue and yellow targets, and participants tap a blue target, there will, on average, be a longer distance to the next blue target than a yellow one. If the blue template only is active, participants will have to move a longer distance. This should result in fewer targets tapped per second than if both templates are active. This means that increased switches

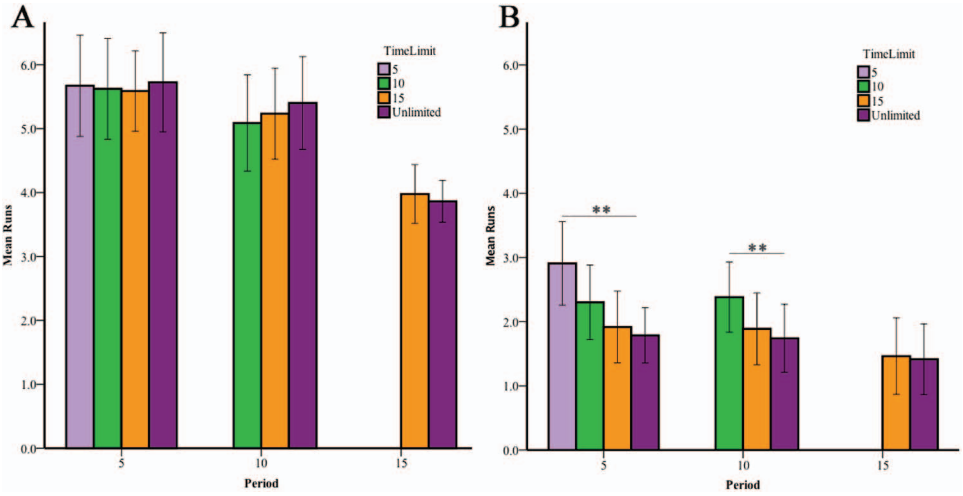

Figure 4. Number of runs by time periods within trials in the different time limit conditions. (A) The results for feature foraging and (B) the results for conjunction foraging. The different colors represent the different time limits and the groups on the x-axis represent the different periods of the trial: 0–5 s, 5–10 s, and 10–15 s. Two stars denote *p* values less than .001 between time limits (see results in the text). See the online article for the color version of this figure.

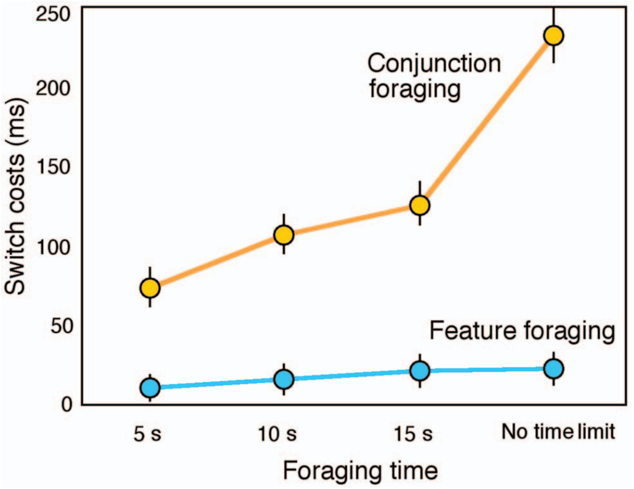

Figure 5. Switch costs calculated by subtracting mean intertarget times (ITTs) on repeats from mean ITTs during switches. The error bars show the standard errors of the mean. See the online article for the color version of this figure.

will allow participants to cover less distance to maximize the number of targets they can tap.

Our previous studies demonstrated that participants rarely switch between target types during conjunction foraging (Jóhannesson et al., 2016; Kristjánsson et al., 2014). This was interpreted as reflecting limits on how many features could be stored in working memory. But this explanation may be too simple. In the current work, the fact that participants switch more often per target and per second when time limits are imposed suggests that more flexible mechanisms may determine foraging strategies. That is, although participants may rarely switch voluntarily without time limits, this might not reflect an inability to do so, but rather that participants simply choose the foraging strategy that best fits their ability given a particular set of task demands. Note that nothing in our data precludes that observers may choose a strategy of having one item in VWM if this suits their goals. But this is clearly not a limit on performance. A number of findings do indeed suggest that VWM representations are flexible. We have already mentioned the findings of Beck et al. (2012), in which observers were able to switch between target representations depending on whether they searched for a single target of one versus two colors. Woodman and Luck (2007) found that there is flexibility in whether the contents of working memory influence attentional selection by task demands (see also Kristjánsson, Saevarsson, & Driver, 2013; Carlisle & Kristjánsson, 2017). There are indeed many examples of such flexibility in the visual cognition literature, such as findings on singleton detection mode (Bacon & Egeth, 1994) and contingent capture (Folk, Remington, & Wright, 1994), showing that this may be a common arrangement.

This idea of flexible working memory guidance is supported by other work from our group. When participants had difficulty controlling the selection interface under time pressure, because they had to tilt an iPad in order to move a player-icon, we saw almost identical switching patterns in the feature and conjunction conditions (Thornton et al., 2015). In another series of studies involving both static and dynamic foraging displays, we removed the penalty that a single error terminated the trial (Thornton, de'Sperati, & Kristjánsson, 2016). This simple modification had substantial impact on conjunction switching patterns. Although there were clear differences between run number during feature and conjunction foraging, we found no evidence of exhaustive runs where a single category was finished before observers turned to the next.

Why do foraging patterns change when time limits are imposed? We propose that during unlimited foraging, participants do not utilize their maximum working memory capacity because of how effortful it is—this would require concentration levels that are hard to maintain during long foraging trials. But we also speculate that during time-limited foraging, participants use short bursts of high concentration where they load WM with the required complex templates, a strategy they avoid during longer duration tasks. When the aim is to maximize the number of tapped targets within a limited time, observers may choose to maintain difficult templates that allow switches, but with unlimited time a less effortful strategy is chosen. By keeping two templates active simultaneously, participants can minimize the average distance between the tapped targets and thereby increase the number of targets tapped per second (as explained above). Over a longer foraging trial (without time limits) this advantage might not be worth the effort as participants will eventually forage through the whole display and tap all the targets.

Individual differences in foraging seen in the work of Kristjánsson et al. (2014) and Jóhannesson et al. (2016, 2017), where a subgroup switched easily between target types, may therefore not reflect their better working memory or attentional inhibition abilities but that these "super foragers" load their memory to a larger degree (see Jóhannesson et al., 2017). Consistent with this idea, 15 out of the 17 participants here switched more often per item during 5-s than 15-s conjunction foraging. Again, comparing the 5-s time limit to the no time limit for conjunction foraging, 15 out of 17 participants switched more often per item with less time, suggesting that the strategy changes imposed here occur for the vast majority of observers.

But how large is this change in behavior? If we compare the 5-s condition with the no time limit condition in Figure 3B, for example, we see that the number of runs per target only increases by ~0.07. However, if this behavior were maintained over a 40-item sequence (as in the unlimited condition) the number of runs would increase by 2.8, a considerable increase in a situation where observers rarely switch at all. We should also note that for the shortest time limit (5 s), there is a large proportion of trials (~30%) in which participants do not switch at all. The most straightforward explanation for this is that the 5-s limit is so short that on some trials only a single category is encountered. While interesting in their own right—as they run counter to the general trend of more switching with less time—the presence of these trials at the very shortest duration suggests that we may underestimate the general impact of introducing time limits.

As noted earlier, our findings are inconsistent with single-template conceptions of visual working memory. Additionally, such theories do not seem particularly plausible from a neurophysiological perspective. A key to understanding this may lie in the proposal of Magnussen and colleagues (1991, 1999), on so-called perceptual memory. This proposal has received considerable support from recent neurophysiological findings that suggest that

VWM storage is achieved within the visual system itself (Harrison & Tong, 2009; Serences, Ester, Vogel, & Awh, 2009). Recently, Christophel and colleagues (2017) argued that working memory representations are stored in distributed networks across the cortex, from sensory areas to parietal and prefrontal cortex. This means that different brain regions contribute to working memory according to their particular function. This distributed functionality does not sit particularly well with proposals of a single active template, which seem to require a dedicated VWM neural apparatus.

Finally, as already mentioned, our time limit manipulation changed the overall task demands in another important way since observers do not need to finish all items in the former condition. This could clearly differentially affect performance—particularly when targets from one category become scarce—and we are currently exploring the impact of such nonexhaustive search in other task contexts. However, the overall pattern of data shown in Figures 3 and 4 makes it clear that this difference cannot account for the total foraging patterns. Even if we ignore the no time-limit condition, there are still differences between the three time-limit conditions, none of which require all items to be found.

To conclude, our results indicate that visual foraging patterns are more flexible than is often assumed. Rather than representing simple fixed capacity limits, a participant's strategy may reflect a more complex interaction between capacity and task demands. Our results may also suggest different ways of conceptualizing working memory, beyond whether it contains a finite number of slots (Luck & Vogel, 1997) or has limited information capacity (Alvarez & Cavanagh, 2004). Instead it might be more useful to think about working memory as a finite resource that is applied flexibly according to task demands (Bays & Husain, 2008; see also Franconeri, Alvarez, & Cavanagh, 2013; Grubert & Eimer, 2013; van Moorselaar, Olivers, Theeuwes, Lamme, & Sligte, 2015; Woodman & Luck, 2007).

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