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Strategies for effective unmanned aerial vehicle use in geological field studies based on cognitive science principles

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ABSTRACT

Field geologists are increasingly using unmanned aerial vehicles (UAVs or drones), although their use involves significant cognitive challenges for which geologists are not well trained. On the basis of surveying the user community and documenting experts' use in the field, we identified five major problems, most of which are aligned with well-documented limits on cognitive performance. First, the images being sent from the UAV portray the landscape from multiple different view directions. Second, even with a constant view direction, the ability to move the UAV or zoom the camera lens results in rapid changes in visual scale. Third, the images from the UAVs are displayed too quickly for users, even experts, to assimilate efficiently. Fourth, it is relatively easy to get lost when flying, particularly if the user is unfamiliar with the area or with UAV use. Fifth, physical limitations on flight time are a source of stress, which renders the operator less effective. Many of the strategies currently employed by field geologists, such as postprocessing and photogrammetry, can reduce these problems. We summarize the cognitive science basis for these issues and provide some new strategies that are designed to overcome these limitations and promote more effective UAV use in the field. The goal is to make UAV-based geological interpretations in the field possible by recognizing and reducing cognitive load.

■ INTRODUCTION

The use of unmanned aerial vehicles (UAVs) or "drones" has seen a dramatic increase within the geological sciences in recent years. A disciplinary search within geology-focused journals using the ISI Web of Science, for example, found 1182 distinct peer-reviewed articles that utilized UAVs for disciplinary research since 1998 (Fig. 1). Approximately 50% of those publications originated within the last 2 yr. Collectively, this research includes nearly every subdiscipline of geoscience. The increasingly low cost of modern UAV technology, in addition to availability of software to render three-dimensional (3-D) models quickly and accurately from UAV imagery, continues to revolutionize both research and teaching endeavors. Although standard digital photography is arguably the most common data obtained from UAVs by geologists, these devices are increasingly outfitted with more sophisticated spectral and geophysical equipment that is leading to new opportunities and emergent research products. In summary, UAVs have rapidly become the "new normal" in the geosciences, transforming field-based research and teaching workflows.

Despite the demonstrably rapid increases in the deployment of UAVs during geological field work, we know of no systematic study to characterize advantages and disadvantages of using UAVs to solve geological field tasks. Beyond the necessary training for licensing, basic safety practices, and compliance with local, state, and federal laws, users have little guidance in the practical strengths and weaknesses of UAVs for field work. Here, we consider the value of UAVs for in-field use and discuss a set of anticipated recurring challenges based on the cognitive demands that UAVs bring to workflows. Limitations on spatial reasoning, including inferring 3-D spatial relations and penetrative thinking, have been documented by combined geological and cognitive science research (Kali and Orion, 1996; Baker et al., 2012; Shipley et al., 2013). Such limitations can have an impact on data collection and inferences in the field (e.g., orienteering, site selection, stratigraphic and/or tectonic inference, etc.), which are all heavily dependent on spatial thinking and reasoning skills (Liben and Titus, 2012). We anticipate that similar issues may arise during UAV-assisted field campaigns, in addition to the possibility of new emergent spatial cognitive challenges that are unique to geoscience field practice with UAVs.

In this paper, we discuss the results of an integrated effort to document, explain, and provide potential solutions for a variety of issues that we argue are inherent to UAV-assisted field work in the geosciences. These efforts were based primarily on: (1) a survey of expert geoscientists attending a UAV operators group town hall at the 2019 American Geophysical Union (AGU) meeting, and (2) observation of three expert geologists undertaking a

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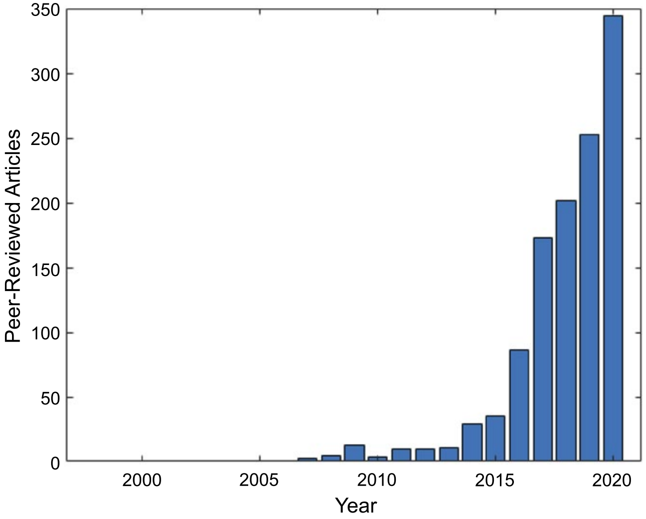

Figure 1. Histogram illustrating exponential rise of unmanned aerial vehicle (UAV) use in geological sciences. Data are the result of a disciplinary ISI Web of Science search in geoscience journals utilizing the words "UAV" or "drones" from 1999 to 2020.

series of predefined field exploration exercises using UAVs in the Mecca Hills area, California, USA. Using the survey results and observation of expert geologists in the field, we identified five major problems that are inherent to the use of UAVs in the practice of geology in the field (as opposed to using UAVs solely for postprocessing in the laboratory), most of which are aligned with well-documented limits on cognitive performance. We review the cognitive science basis for these issues and suggest some new strategies to overcome these limitations and promote more effective UAV use in the field. Considering UAV usage from the perspective of cognitive science can provide the geoscience community with ways to better understand how UAVs can further science as well as directions for training, including the challenges faced by novice geologists, why those challenges never completely disappear, and potential learning opportunities to support professional growth for field geologists.

UAV USERS SURVEY FOR GEOSCIENCE

To understand the types of geoscience field tasks that UAVs are being used to support, and to capture possible use cases that are not represented in the published literature, we surveyed expert geoscientists (*N* = 43) attending the UAV Operator Group town hall at the 2019 American Geophysical Union fall meeting. See Item 2[1] for a copy of the UAV geoscience user survey questions. Participants reported various specializations within geoscience, including structural geology, hydrology, atmospheric science, natural resource management, agriculture, and earthquake and volcano response teams.

UAV users reported a wide range of experience (0–19 yr), and the majority (88%) used low-cost, commercial systems. Although some users (43%) did report using the UAV to make in situ decisions, such as where to explore next, almost all users (92%) reported that they employed the UAV for collecting photos. When asked to rate how useful UAVs were, the responses reflected the purposes the participants initially reported; most found the UAV useful in photogrammetry and mapping but less useful in planning of field work. Several challenges were reported by novice UAV users, including: (1) understanding what they were seeing (i.e., the quantity of information felt overwhelming); (2) sun glare when viewing the UAV video during flight; and (3) challenges with spatial orientation (i.e., tracking where the UAV is in space and the direction it is looking). Participants reported the frequency of experiencing these challenges was reduced with experience, but not eliminated.

The findings from the survey highlight the potential benefits of UAVs for field-based geoscience interpretation. At present, UAVs are mostly used to collect photos and videos that can be used in analysis at a later time. They are less frequently employed as tools to make near-real-time decisions or otherwise support understanding an area for geology practice, despite their potential value in speeding decisions about where to go in an area and to provide perspectives not available on the ground or from satellite imagery. These findings provide an opportunity to further explore the cognitive opportunities and constraints for UAVs in geological field work. Toward that effort, we describe observation of expert geologists (authors Pavlis, Cooke, and Fagereng) using a UAV in the field during a controlled exercise that moved the use of UAVs beyond photography into more active roles in field work.

OBSERVATION OF EXPERT GEOLOGISTS DURING UAV DEPLOYMENT

To illustrate how field geologists use UAVs in situ to support initial exploration and interpretation of an unfamiliar locale, we observed three expert geologists conducting UAV-assisted field investigations in the Mecca Hills area, southern California, USA (see Supplemental Material, footnote 1). This area records a complex history of sedimentation, folding, and faulting associated with the San Andreas fault, and it is importantly almost entirely exposed and visible from the air. The research focus and experience of these geologists were variable, although all three may broadly be described as structural geologists. Some were primarily field

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[1] Supplemental Material. Item 1: Field-Based UAV Protocol for Geoscientists. Used in the Mecca Hills with field geologists at three locations. Provides goals, instructions to the geologist, and questions asked of them before, during, and after their flights. Item 2: AV Geoscience User Survey. Administered to expert geoscientists attending a UAV operators group town hall at the 2019 American Geophysical Union (AGU) meeting. Includes questions given in digital format at that town hall. Please visit https://doi.org/10.1130/GEOS.S.21225653 to access the supplemental material, and contact editing@geosociety.org with any questions.

researchers, whereas others were primarily laboratory researchers, they spanned early to late career, and they had differing levels of familiarity with the Mecca Hills and with using a drone for structural interpretation. Although our sample is small, we attempted to make it representative of the breadth of possible geologist UAV users to help ensure our observations were generalizable to the community.

The three geologists were given a series of specific tasks aimed at investigating Mecca Hills geology. The tasks included interpreting the structures in a large-scale vertical outcrop that was visible from the ground but not safe to climb on, mapping a structure in a maze-like highly eroded topography with limited vista views, and a free-form exploration akin to an initial visit to an area, where the geologists were allowed to choose where and when to fly the UAV after driving along an ~12 km segment of Box Canyon Road that cuts through the lithological units of the Mecca Hills. See Supplemental Material (footnote 1) for a copy of the protocol for field tasks, including interview questions. Each of the tasks provided opportunities to make real-time decisions and interpretations, moving beyond the photogrammetry for which UAVs are typically utilized in geology field work.

During these tasks, the UAV was piloted by a separate person (a trained UAV pilot). Having a pilot allowed the geologists to devote cognitive resources and field time to consider science goals, rather than having to share limited resources and time by managing the piloting. It was also practically necessary since some of our experts had never flown a drone before and were not appropriately licensed to do so. The experience for the geologists was similar to directing the driver of a land vehicle on where to go, how fast, and when to stop while observing and interpreting rock outcrops. While the UAV was in flight, the geologists watched the UAV's live video feed on a 9.7 in. (24.6 cm) iPad tablet and directed the UAV pilot to move as necessary. On the iPad, the geologist was able to view the camera view from the UAV, the UAV flight path relative to the position of the pilot, the UAV altitude, and the UAV speed. The DJI Mavik Pro UAV (https://www.dji.com/mavic/info) used for these exercises was limited to traveling no more than 750 m from, and 120 m above, the controller. Individual flight times were limited by battery life to ~25 min, although the geologists could choose to end a flight earlier.

We recognize that just as many geologists drive themselves and do science simultaneously, many will also fly UAVs themselves. Geologists attempting dual roles should be prepared to experience additional cognitive load beyond that described in this paper. Alternatively, geologists that act as their own pilot may allow better spatial awareness of the UAV position; this viewpoint was expressed by some of our practitioners. Additionally and importantly, the findings from the UAV users survey support anecdotal evidence that many of the challenges of piloting are reduced (but not eliminated) with practice. The trade-off between reduced cognitive load gained by relinquishing those responsibilities to a well-trained colleague and the spatial awareness that may be gained in self-piloting is a decision that will need to be made by the geologist.

The geology of the Mecca Hills is often described as three distinct structural blocks (the platform, central, and basin blocks; Fig. 2), all of which are visible driving through Box Canyon along Box Canyon Road (Sylvester and Smith, 1976, 1987). At the north edge of the Mecca Hills, the platform block is defined by nearly flat-lying sediments of the Pliocene Palm Spring Formation. A sliver of the underlying Orocopia Schist (Cretaceous–Paleogene) basement is also exposed near the northernmost end of Box Canyon, where it forms a buttress unconformity with overlying Palm Spring sedimentary units. Immediately south of the platform block, there lies the central block, which is defined by an abrupt transition to highly deformed stratigraphy of the Palm Spring Formation and underlying Miocene Mecca Formation that define a series of anticline/syncline pairs of varying amplitude and frequency. These folds are locally cut by series of high-angle, reverse-oblique slip faults defining the Painted Canyon fault zone, which forms the boundary between the platform and central blocks. The transition from the central block to the basin block is defined by distinct folding and faulting of the Palm Spring Formation along the San Andreas and Skeleton Canyon faults.

Strategies Observed

Here, we describe the common strategies employed to some extent by all the experts we observed in the field. At least some of these strategies are similar to, or were anticipated by, previous research utilizing non-UAV-based aerial photography (e.g., Putnam, 1947; Delaney and Pollard, 1981; Rawnsley et al., 1998; Johnson et al., 2014). These strategies highlight specific difficulties and opportunities encountered during UAV-based operation, namely, the pronounced versatility in flight path and the real-time information provided. The mechanism and intent of each strategy were discussed with the experts during postflight interviews in the field, which were recorded by video. Many of the strategies that the geologists employed during their UAV flights were directly analogous to traditional on-foot strategies but adapted and augmented by the affordances of a flying agent, which is comparatively free of travel and terrain limitations. Although the strategies described below represent a large majority of those employed by the observed experts, this list is not intended to be exhaustive.

(1) Following an observed or inferred contact: Akin to traditional field geology, the expert geologists spent considerable time using the UAV to follow or trace observed and/or inferred contacts or other linear structures. Employing this approach with the UAV, from the experts' reported perspective, allowed them to visually cover ground much more quickly than by pedestrian travel. Moreover, the UAV can travel to areas that from a practical perspective are inaccessible by foot. For example, Figure 3 illustrates a flight path taken by one of the experts, where the UAV was used to estimate the strike of the Skeleton Canyon fault near the boundary between the central and basin blocks of the Mecca Hills. Much of this flight path would be extremely arduous (nearly impossible) to traverse by foot. Here, following the fault trace helped the expert to maintain their sense of location, offering a "handrail" to move around in the geology without getting lost.

(2) Traveling perpendicular to strike of an observed or inferred contact: Also similar to approaches

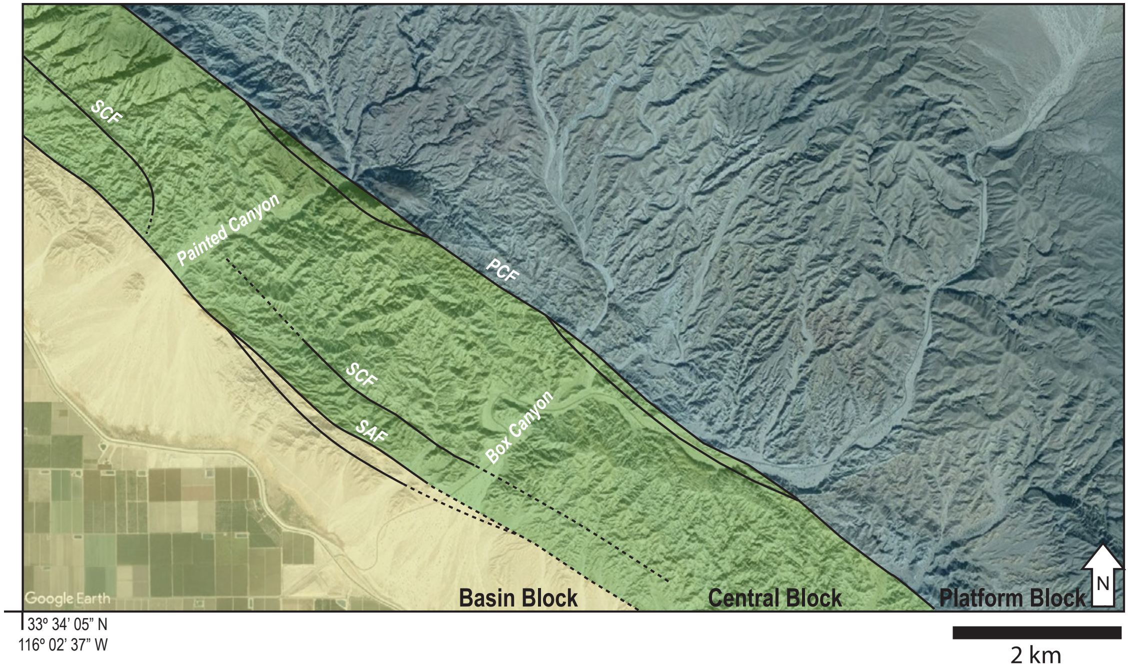

Figure 2. Satellite imagery of the Mecca Hills, California, study area showing major faults (SAF—San Andreas fault; SCF—Skeleton Canyon fault; PCF—Painted Canyon fault) that delineate major structural units (yellow—basin block; green—central block; blue—platform block). Satellite imagery, map data: Google, Landsat/Copernicus.

in field geology, the expert geologists spent flight time repeatedly traversing across the strike of contacts or other linear structures once they were comfortable with their location in map view (i.e., after following the contact/structure for some distance in the landscape). This strategy in particular is enhanced by UAV use, as traversing across the strike of structures on foot in the Mecca Hills is strictly limited by the availability and placement of transverse canyons given the relatively steep terrain. A drone is capable of crossing canyons that would be time consuming, physically difficult, or even impossible to traverse on foot. It also allows the geologist to maintain sight of the suspected contact, rather than to continuously search for and reorient to the contact once elevation is regained. For example, Figure 4 shows a flight path where the geologist guided the UAV to find the Skeleton Canyon fault and then make a long path that crossed perpendicular to both the Skeleton Canyon fault and another unnamed fault in a search for variations in bedding orientation in the vicinity of an inferred linkage between the Skeleton Canyon fault and the unnamed thrust fault.

(3) Gaining a new perspective/vantage point: The angle at which one views a surface influences the analysis of penetrative features, and some features are more readily interpreted from specific vantage points. Geologists often overcome this obstacle on foot by climbing to gain a new perspective, but this potential is limited by the surface of interest, local topography, time, and physical capabilities of the observer. The advantage of this approach is particularly apparent in estimating the orientation of planar features, which is best accomplished from a perspective that is within the plane of interest. The UAVs allowed the expert geologists to observe stratigraphy, geological structures, and relations among features (e.g., crosscutting relationships) from nearly any angle, greatly aiding in orientation estimation and interpretation. Figure 5 shows a flight path where the expert geologist utilized the UAV to gain elevation to better observe an exposure of the Painted Canyon fault, which places the Miocene Mecca Formation on top of the Pliocene Palm Spring Formation. Once at a sufficient altitude, the geologist was able to travel to look down plunge at the geological feature, rather than viewing it obliquely, which could have led to incorrectly estimating the orientation or the shape of the 3-D structure.

Although most of the strategies employed by the expert geologists using the UAV aligned with on-foot approaches in the field, various problems that are unique to UAV-based investigation arose. These issues were of sufficient magnitude that the expert geologists all reported that they were frequently unable to solve problems to their satisfaction by using the UAV. This finding is notable given the variety of advantages provided by the UAV when

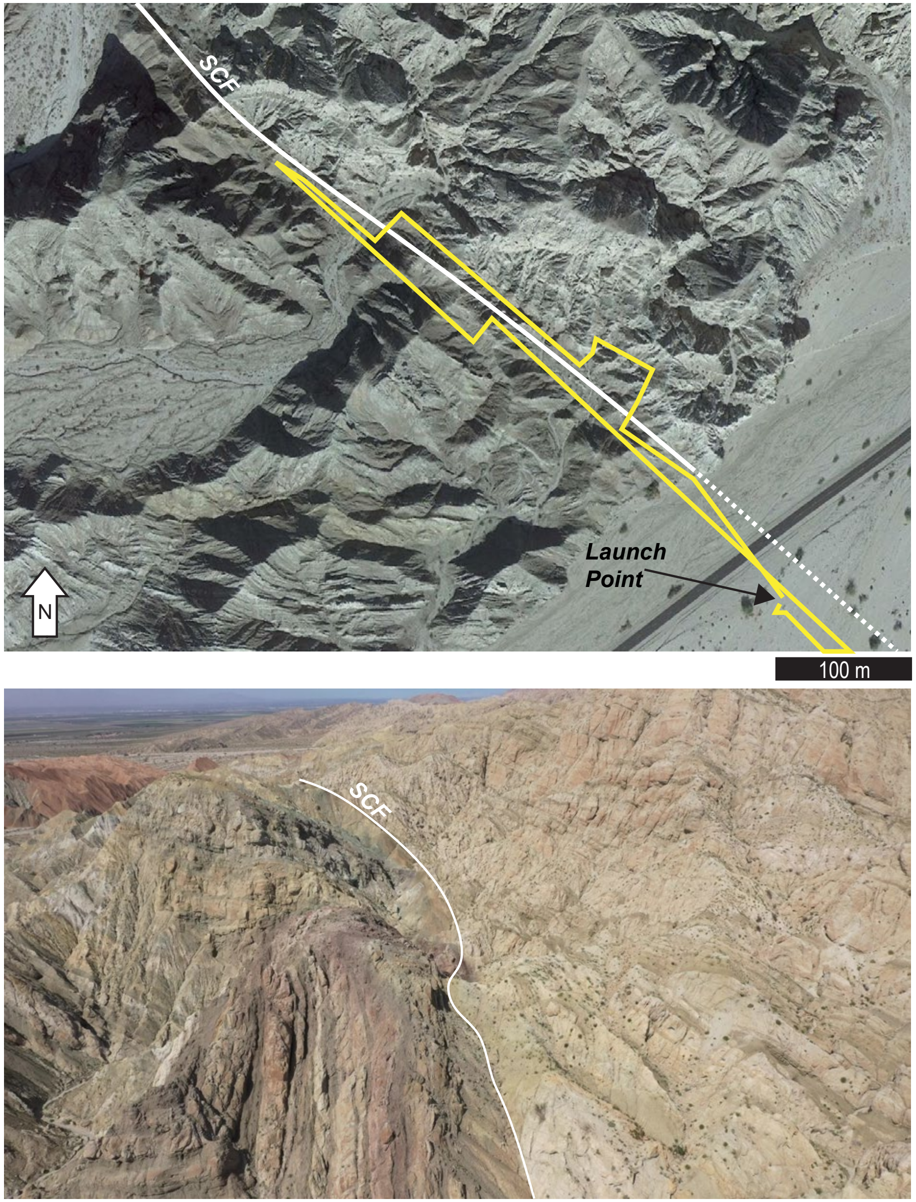

Figure 3. (Top) Unmanned aerial vehicle (UAV) flight path (yellow) shown on satellite imagery as an expert geologist attempts to trace the path of the Skeleton Canyon fault (SCF; white) near its intersection with Box Canyon Road. Satellite imagery, map data: Google, Landsat/Copernicus. (Bottom) Image of the Skeleton Canyon fault as observed using the UAV's onboard camera/video feed; 33°35′02.22″ N, 115°58′58.96″ W.

compared to traditional field approaches and the exceptionally well-exposed nature of the geology in the Mecca Hills. Likely, some of these concerns would have been addressed if the geologist could have explored on foot. Two immediate hypotheses may be posed to explain the experts' difficulties, which are worth considering for supporting UAV use without requiring on-foot follow-up of all flights. First, the UAV does not generally provide observations at the scale and rate with which geologists are familiar, which prevents the geologists from fully utilizing their past experience and training to evaluate a new area. Second, the UAV changes the typical workflow of the geologists, which requires a significant time for mental adjustment. Below, we speculate that the difficulties experienced by the expert geologists reflect a variety of cognitive constraints on processing the information coming from the UAV in real time.

HYPOTHESIZED COGNITIVE ISSUES INHERENT IN UAV-BASED GEOLOGY

The results of our community survey and observation of experts in the field allowed us to identify five major challenges to making UAV-based geology observations: (1) rapid and unconstrained variations in the point of view; (2) rapid variations in the scale of observation; (3) information overload; (4) disorientation about the UAV location and/or the direction it is facing; and (5) time pressure associated with limited battery life and/or flight time. Although there are interactions among these challenges, we address each separately for clarity. For each, we articulate the problem and review their potential cognitive origins. In the subsequent section, we then consider how the geology community could reduce the impact of these challenges.

Rapid Variations in Point of View

The Problem

Many geological features are planar (e.g., bedding) or have an important planar property (e.g.,

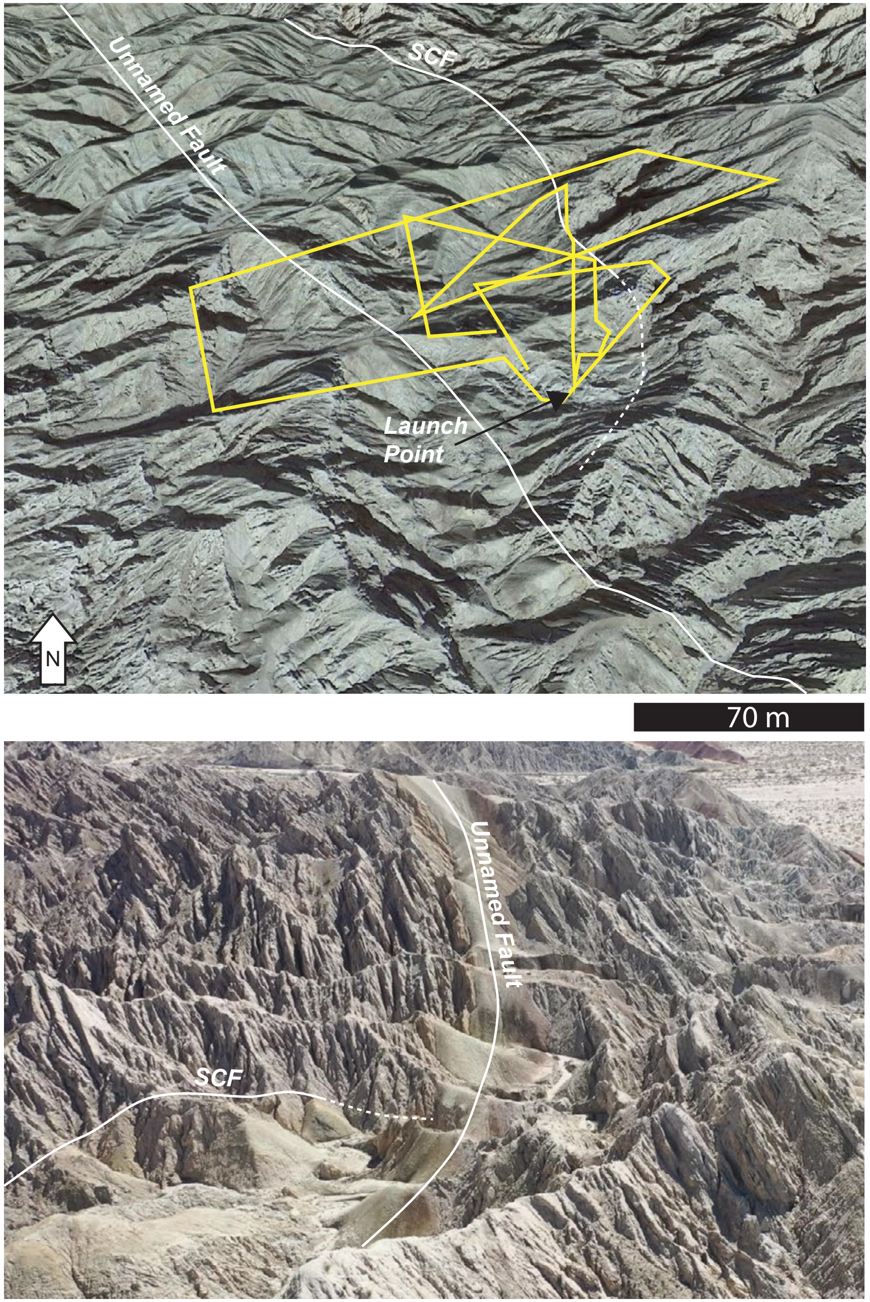

Figure 4. (Top) Unmanned aerial vehicle (UAV) flight path (yellow) shown on oblique satellite imagery as an expert geologist traverses perpendicular to the strike of two exposed faults (Skeleton Canyon fault "SCF" and an unnamed fault in white) near their inferred intersection. Satellite imagery, map data: Google, Landsat/Copernicus. (Bottom) Image of the two target faults as observed using the UAV's onboard camera/video feed. Thickness of the unnamed fault is ~10 m; 33°36′43.04″N, 116°01′36.10″ W.

axial plane), and thus some viewpoints are privileged for optimally assessing the structures. At an outcrop scale, an ideal viewpoint may sometimes be achieved by physically moving to change one's viewpoint. For larger outcrops and on a regional scale, there is rarely a fortuitous location that allows the geologist to achieve optimal viewpoints. As a consequence, geologists often first map locations of lithological and/or orientation changes and then use the map data to make inferences about forms. This approach transforms the ground-level viewpoint, which may be poorly aligned with a structure's orientation, to a bird's-eye view where orientation may be readily observed. UAVs offer a new solution to this perspective problem, as they can be flown to any location within the plane of a planar feature (e.g., to get a downdip or in-plane, cross-section view). A current approach to this problem has been the use of 3-D terrain models (e.g., Bemis et al., 2014; Pavlis and Mason, 2017), but, in many cases, these perspective views could be readily achieved with a live UAV feed on site.

Ironically, the very feature that makes UAVs so attractive for field geology is the source of one of their most significant problems; the viewpoint can (and in practice, does) change rapidly. For example, the DJI Mavik UAV used during our observation of experts can reach its maximum altitude of 120 m in less than 30 s following takeoff and spin 360 degrees in less than 5 s, and it is capable of moving at ~65 km/h in any direction, regardless of which way it is "facing." Even after flying UAVs in one location for an extended period of time, the geologists in our field test reported that these quick changes resulted in significant disorientation. For the novice UAV user, much flight time is lost simply trying to (re)orient one's self before data collection

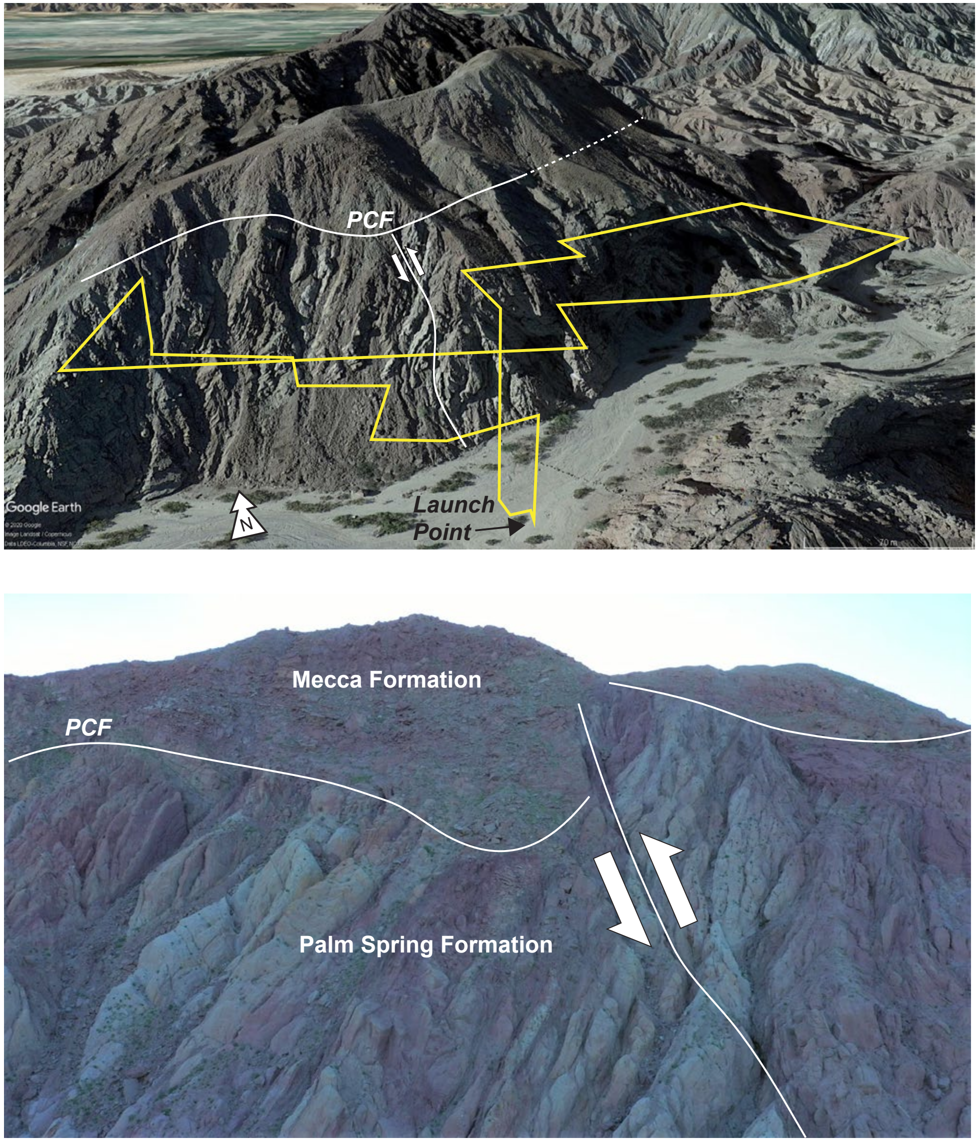

Figure 5. (Top) Unmanned aerial vehicle (UAV) flight path (yellow) shown on oblique satellite imagery illustrating an expert geologist using the UAV to gain elevation to better observe the relationship between two faults (white; Painted Canyon fault "PCF"). Satellite imagery, map data: Google, Landsat/Copernicus). (Bottom) Image of two intersecting faults as observed using the UAV's onboard camera/video feed. In the upper panel, the height of the cliff face in the foreground is ~220 m. In the lower panel, the maximum thickness of Mecca Formation in the image is ~40 m; 33°37′03.03″ N, 115°59′57.00″ W.

can begin in earnest. Thus, the flexibility of UAV motion and point of view has several consequences for humans that may be anticipated based on the cognitive challenges associated with rapid changes in view location.

Cognitive Science of Processing Information from Varying Viewpoints

Why are some viewpoints better than others, and why is changing viewpoint disruptive? There are two, related answers. First, although it is trigonometrically possible to recover 3-D forms from any viewpoint if the distance, orientation, and location of the form relative to the viewpoint are known, in practice, the human visual system struggles at this task. The phenomenal experience of the world may be of metric precision (e.g., represented as a ratio scale, such that a doubling of a property in the world is represented as an exact doubling in the mind). The visual system, however, only provides precise metric information for some visual features, such as length and orientation in the frontal plane (i.e., the plane perpendicular to the observer's viewing vector). Other features, such as slope, might better be thought of as ordinal (e.g., an ordered scale such that a doubling of a property in the world would only be represented as greater than the original property) with substantial absolute errors (e.g., Proffitt et al., 1995). Thus, judgments about subtle differences in the orientation of a fold limb are best made from a viewpoint where one can assess the symmetry in the frontal plane (i.e., by having a view within the axial plane of the fold), without having to mentally correct this input using imprecise orientation information.

Second, recognition of forms is also orientation dependent. Although it is possible to imagine recognition processes that are viewpoint independent (e.g., Biederman, 1987), human recognition appears to be closely tied to the original orientation of the experienced viewpoint (Tarr et al., 1998). Even short flights result in viewpoint changes that drastically change the orientations of geological features and thus alter their recognizability. In laboratory tasks, shifting a view more than 45° results in difficulty identifying the previously familiar objects and scenes (Tarr et al., 1998; Diwadkar and McNamara, 1997). We hypothesize that a UAV's atypical perspective and rapid variations of viewpoint can challenge the geologist's ability to identify structures, including those directly visible from the ground. Note that we are not suggesting an expert cannot identify a fold from the air. Rather, we are suggesting that experts may have trouble recognizing specific features as ones that have already been seen when approached from a new direction: e.g., which fold/fault/mud layer is this? Is this a new one or one I have seen before?

Finally, the mind can accommodate a new perspective by mentally reorienting the object or scene, but the mental operation takes time (Tarr and Pinker, 1989), is limited in capacity (Shepard and Metzler, 1988), and works better for single objects than for multiple objects (Hegarty and Waller, 2004). The incessant need to mentally adjust the landscape perspective as the UAV changes location and orientation may in part explain the rushed feeling experienced by geologists when they begin using UAVs in the field (more below).

Varying Spatial Scale

The Problem

Traditional field work generally has a limited scale of observation constrained to what can be seen from the surface of Earth. When larger areas are considered, satellite photos or maps are typically employed. For inspection of outcrops of particular significance in greater detail than satellite imagery allows, sometimes there is a fortuitously accessible overlook available. However, hiking/climbing to these locations almost always requires a significant time investment (and sometimes risk) and so must be of sufficient value to warrant the investment. When experts engage in such activities, they generally have little difficulty maintaining their sense of orientation within the field area, and they readily grasp how the outcrop of interest fits into other geological features in the area. Using a UAV, which reduced the time investment of hiking and climbing, also reduced the expert's sense of orientation. This effect possibly occurred because the visual spatial information was impoverished relative to being present in person and moving much slower on foot. Disorientation did not appear to occur simply by changing spatial scales. Experts flew the UAV to inspect nearby outcrops from the air, descending or ascending to observe the feature within a range of contextual scales, and did not become disoriented. However, often in the course of a series of such maneuvers flying from one outcrop to the next, an expert would report being disoriented and occasionally completely lost, including being unsure about where the UAV was and how it was oriented relative to themselves or any other location in the area.

Cognitive Science of Mental Scaling and Reorientation

There is only modest research on the problem of scale invariance of recognition (being able to recognize something as the same when seen larger or smaller than the original), although recent research has found that changes in scale are much less disruptive than changes in orientation (Han et al., 2020). This situation leads to the obvious question: Why did experts experience disorientation when simply changing the scale of observation of some features? The realities of geological field work are such that significant changes in the scale of an observed point are rarely achieved in the absence of at least some change in the viewpoint. That is, an observation of an outcrop from the air may, by definition, only be achieved by gaining elevation and looking down. Here, we consider the potential for combined scale and point-of-view changes occurring over relatively short time scales that disrupt the expert's sense of location and orientation of the UAV within the field area.

We suspect that both the amount of time and the physical movement through space required to effectively change location and scale of observation when hiking may allow the observer a different quality of mental representation of the world. This quality contrasts with the similar changes of scale accomplished by changing a UAV's altitude far more rapidly. The act of moving one's self through space maintains better representation in memory of the space than when one is passively moved through the space. However, accurate memory is most disrupted by having the space move around a stationary observer (Holmes et al., 2018). This distinction may effectively be the experience when the geologist is stationary and observing the changing perspective of the UAV on a display. Thus, it is possible that experts' difficulty arises from both being stationary and having a poor sense of how the UAV is moving through space, a challenge unmitigated by whether the user pilots the UAV or not (Holmes et al., 2018). The extent to which humans can adapt to learn to navigate and explore in a volume is an open question. Humans are evolved to navigate on surfaces, and the environment in which one normally navigates heavily influences one's skill at using spatial information (Holbrook and De Perera, 2011). How best to support human navigation within a volume with the skill of flying and swimming organisms is an important question for human-machine research.

Flying a UAV to survey an area requires geologists to maintain self-orientation, their sense of where they are and their view direction, to appropriately integrate spatial information as it becomes available. Geologists must simultaneously determine the direction they are facing and the direction in which they want to move to get to where they want to be (Cheng and Newcombe, 2005). These issues, compounded by making observations as they move, may alter the priority of the initial destination. In conventional geological field work, a geologist likely uses point cues (e.g., the sun or a tall mountain) as well as gradient cues (e.g., slope) to orient and, if necessary, reorient themselves (Newcombe et al., 2015). Some psychologists have argued for a third type of spatial information that becomes important when orientation breaks down or is lost: The observer can reorient using the local geometry of the environment, which is impervious to environmental fluctuations (e.g., changes in light due to where the sun is, or time of year; Cheng and Gallistel, 1984; Cheng and Newcombe, 2005). Reliance on a space's geometry for self-orientation could be problematic with a UAV because it can move out of the visually familiar geometry on the small scale of the local launch space (e.g., a canyon) to the new and relatively unfamiliar landscape-scale geometry in which an elevated perspective minimizes variations in height in the landscape.

In the absence of information about the observer's self-motion and a full visual field, all three types of self-orientation cues are limited when using a UAV. Self-orientation is easier to maintain with active motion, where the observer is moving through the world, relative to passive motion, where someone else controls the motion (Rieser and Pick, 2007). While UAV flights are partially observer-controlled, they lack embodied motion, as well as the feedback that motion provides from joint, muscle, and vestibular senses—leaving only visual feedback. Remote flying disrupts the familiar coordination of action, perception, and representation that is part of a system that helps people gracefully move through space (Rieser and Pick, 2007). While the optical information available from the UAV is mathematically sufficient to accurately update position, humans are imperfect integrators, and errors can accumulate. Furthermore, research on mental models of space (Radvansky et al., 2010) has found that humans develop rich but temporary representations of space that are discarded when action in the space is no longer anticipated (e.g., when one leaves a room). Whether through accumulated error or active loss of a representation, catastrophic failure occurs when the user loses all sense of the location and orientation of the UAV.

Information Overload Caused by Rapid Variations in Viewpoint and Scale

The Problem

Although a geologist may enter a field area equipped with a wide variety of geologic maps and satellite images, the disparity in scale between these points of view is large. UAV-based observation in the field offers the opportunity to create a middle ground between the two scales (1–10 m on foot and 100–1000 m from satellite imagery) of observation, allowing detailed lithological variations to be viewed over a much larger area in conjunction with map-scale structural details. However, effective use of a UAV to integrate satellite and on-foot scales requires combining information over time from different locations and from different scales. When combined with the substantial speed of modern UAVs, which can cover large portions of a field area very quickly, the potential to make accurate geological observations is limited by the geologist's capacity to direct the UAV to goal locations and assimilate the information as it becomes available. The expert geologists that we observed using UAVs to develop structural interpretations in the field consistently reported being "overwhelmed" by the rate of information delivery. They seemed to be in a state of information overload, with too much information coming in too rapidly. The sensation of information coming in "too fast" contrasted with receiving information and making observations at a rate controlled by terrestrial logistics and from a particular viewing perspective determined by the terrain.

Cognitive Science of Information Overload

The human mind has a relatively small limit on what it can actively work on at any given time. In contrast to our ability to store large amounts of content for long-term retrieval, the limit for content that can be actively used for most people is ~3–4 items (where each item is, e.g., the memory of an object or event; Cowan, 2008). This limit is referred to as "working memory." In the context of flying a UAV to interpret local geology, experts will need to remember their observations and the spatial locations of the relevant features. The working memory limitations severely restrict the number of observations that can be combined into a regional interpretation. Increases in the complexity of structural relations and in the complexity of UAV flight paths will further increase demands on working memory. Once the working memory limits are exceeded, the experience may be interpreted as information coming in too fast.

Experts have adapted to working memory limits by building large and sophisticated memory chunks—what counts as one item in working memory can change with expertise. Chess experts, for example, reason in chunks that involve multiple pieces and sequences of multiple moves (Chase and Simon, 1973). It is likely that as familiarity with a research area develops, chunks will also develop. One example of a chunk could be an oft-flown UAV path that successively visits a series of outcrops, or a collection of outcrops in the landscape that reveal a large-scale structure. In this example, more information can be assimilated with each subsequent flight.

Getting Lost with Respect to the UAV's Position in Space

The Problem

In traditional field work, experts need to stay oriented relative to their field area to ensure that they are appropriately integrated into the development of both maps and mental models as they make observations. Then, at the end of a day of working in an area, the geologist will need to return to their car or campsite. While students may sometimes struggle with these navigational challenges, the experts generally stay oriented over the course of the day and can get back to the car or other relevant waypoint without incident. Notably, while flying the UAV, there was much conversation about the location and orientation of the UAV: "Where is the UAV?" "Which way is it looking?" "Is that us in the camera?" Occasionally, there would be a complete failure to keep track of where the UAV was, and it would have to be reoriented in some way (e.g., flown up to an elevation where it was visible or back to the launch location), even though the flight path was visible on the iPad screen. These events represent catastrophic failures in navigation, including having no idea where the UAV was. In short, getting "lost" is quite easy for both novice and expert UAV users.

Cognitive Science of Navigation

Humans and most animals have multiple strategies for locating themselves in the world and maintaining that sense of location as they move (Gallistel, 1990). In familiar spaces, landmarks may serve to keep one oriented. In unfamiliar places, broadly two strategies are employed. First, as one moves, one may use motor information (e.g., I walked so far and turned left and then walked another segment) to maintain an integrated representation of how far one has moved from a known point. Similarly, sensory input from motion (e.g., optical sense of motion and middle ear detection of acceleration) can be combined and accumulated to estimate one's location. Path integration in the absence of self-generated action is poor (Rieser and Pick, 2007), perhaps in part because optical estimates of motion alone are imprecise. The catastrophic failures of location reported by the geologists may represent accumulated error. In the case of UAV use, these accumulated errors may on some level arise from all the above sources of difficulty (e.g., variations in point of view, scale, unfamiliarity navigating a volume, and information overload). Although some animals are capable of remarkable feats of path integration (e.g., desert ants; Müller and Wehner, 1988), unpracticed humans may be limited in the number of path segments and turns they can remember and combine (Loomis et al., 1999).

Time Pressure

The Problem

In addition to the problems above, UAV-based observation during geological field work also imposes a technological time limit within which detailed observations must be made. Specifically, all commercially available UAVs are subject to restricted flight times dictated by battery charge. This limitation, in conjunction with the above sources of difficulty, results in feeling "rushed" while the UAV is in flight. We refer to this mental challenge as "time pressure."

Time pressure appeared to be a component of nearly every flight, although the "purpose" of the flight likely played a role in its severity. For example, flights conducted for the purpose of simple reconnaissance appeared to be less affected by time pressure than were flights conducted with the goal of making detailed sketches or verifying important interpretations. Interestingly, this issue was persistent for all of the examined experts despite the knowledge that enough spare batteries were available to ensure ~3.5 h of flight time each day. Moreover, the expert geologists rarely utilized all of their total available flight time, as spare batteries were generally still available at the end of each day.

Cognitive Science of Working under Time Pressure

The mental workload of a task may place stress on the actor. In UAV-based geological field work, each task must be completed in unfamiliarly short times. The time limit imposed by the battery may cause a geologist to proceed faster than they might be comfortable processing information. Even if the geologist is not intentionally rushing, UAVs can fly through an area much more quickly than a geologist could walk the same distance. As the speed increases at which tasks, such as making sense of geological features, are required, the probability of making an error is also increased (Proctor and Vu, 2009). On top of the increased processing demand imposed by limited time and increased rate of information inflow, there is a further increase in the mental workload introduced by the computer interface that transmits information between UAV and geologist. Most such human-computer, interface-based tasks have been shown to cause more mental fatigue and thus be more stressful to the user than analog versions of the same tasks (Trimmel and Huber, 1998). To navigate the increased task demands, geologists may exert additional mental effort to maintain performance, which may further increase stress (Szalma and Hancock, 2009). In turn, this situation results in additional decreases in efficiency and increases in errors.

Navigation using a computer interface can also increase stress when the information provided by the interface fails to match expected locations (e.g., driving quality is reduced and feels more stressful when global positioning system [GPS] information is erratic; Morgan and Hancock, 2011). A familiar feeling to most drivers, being lost while also trying to recalibrate a GPS system may have an analog in the stress experienced flying a UAV. In the UAV case, practitioners are asked to make geological interpretations (e.g., the equivalent of driving) while also keeping track of personal and UAV locations in physical space (e.g., the equivalent of recalibrating the GPS).

CURRENT STRATEGIES FOR UAV USE BY GEOLOGISTS

The survey results indicated that many geologists avoid the use of UAVs for real-time investigation, perhaps to avoid grappling with the cognitive challenges previously discussed. Instead, many use post hoc photogrammetry techniques developed in the last few years to produce photo-realistic 3-D terrain models (for examples, see Pavlis and Mason, 2017; Brush et al., 2018; Bemis et al., 2014). Pavlis and Mason (2017) described how these methods allow unlimited viewing of a field site from any arbitrary angle, thus eliminating the information overload from real-time UAV video feeds and also allowing more time to solve problems than conventional field workflows. The problem, however, is that photogrammetry methods require initial site assessment, ground control placement, flying the mission to acquire imagery, processing the data, and then usually revisiting the site for additional ground control. In total, the logistics require significantly more effort than conventional field projects. Specific workflows vary, and different sites produce different logistical challenges, but it is clear these UAV-intensive photography methods are inefficient for a wide range of field problems where the geologic structure, terrain, or both do not require these advanced methods (e.g., Brush et al., 2018).

In our field area, geologists used real-time UAV information and did so in a way that mitigated cognitive loads, although skill in minimizing load developed over time. The geologists often limited the data feed rate in two ways: (1) stopping and hovering and (2) returning the UAV to the area where the geologist was located. "Stop and hover" is analogous to existing methods used by geologists using a helicopter for field work. In flight, the geologist sees a feature, tells the pilot to stop, circle, and/or hover over the site, and records and develops an initial interpretation of the feature via sketching, notes, photographs, or some combination. During real-time helicopter flights, the geologist generally feels "rushed" in their analysis, either because of economics (cost of helicopter flight time) or time constraints on the machine (fuel or other operational details in the field party), as we saw in our observation of UAV users. Although this has not been explored in literature, we surveyed several geologists (*N* = 8; see Acknowledgments) who frequently use helicopters in the field, all of whom agreed upon feeling rushed while in flight from economic or time-related constraints.

The second approach, returning to base, has no clear analog in existing methods. It is, however, a sensible if not obvious approach with a UAV. This task can be performed by simply pushing a "home" button on the controller and the UAV will quickly return to base, saving potentially valuable battery life (and future flight time for the day) and effectively resetting any accumulated location error. This approach can be used to provide the field geologist time to digest information and can provide an opportunity to review video recorded by the UAV.

NEW STRATEGIES FOR UAV USE BY GEOLOGISTS

We propose a set of strategies, some of which are already being utilized by geologists using UAVs, to mitigate the challenges of UAV use during field work. The first three strategies (Figs. 6 and 7) are useful because they eliminate variables from individual UAV flights, mitigating the effects of rapid variations in scale and viewpoint. The next set of strategies is intended to reduce the probability of getting lost or to rapidly recover position certainty after becoming lost, which is a particular problem in unfamiliar terrain and in situations for which line of sight cannot be maintained. The final set of strategies includes ways of cognitively offloading aspects of the UAV flight, which will reduce stress and allow the geologist to concentrate on the geology.

Guiding the UAV in a Way that Reduces Cognitive Load

As discussed earlier herein, a significant source of increased cognitive load during UAV operation occurs when there are rapid variations in view direction, vantage point, and scale. Rapid changes in these parameters are likely to result in failures to recognize parts of the landscape when seen from new positions (Fig. 7). One way of reducing cognitive load is to hold one or more of these variables fixed during flight. We have found, for example, that holding a constant view direction while flying on a linear constant-elevation path (referred to as a tracking shot in storyboarding; Fig. 6), where the vantage point varies due to translation of the UAV in space, is a useful strategy for simplifying UAV-based observation. Alternatively, the UAV may change elevation and view direction without changing location in the landscape (referred to as a pedestal shot in storyboarding; Fig. 6). Similarly, in some situations, it is useful to keep the UAV's position in space fixed and move the camera by pan (rotate the UAV in a horizontal plane) or tilt (rotate in a vertical plane using the gimbal) of the camera (Fig. 6). Conceivably, more than one of these strategies can be employed in sequence within a single flight, but sufficient time should be taken between distinct strategies to allow better comprehension of orientation and position.

Extended experience in an area will provide the geologist with familiarity of the geology seen from above as memory accumulates and the novel becomes familiar. To speed up this process, a geologist could proactively guide the UAV in early exploration to increase the chances of recognizing important parts of the landscape (described more in the next section). Viewing an object from multiple perspectives can help to develop a 3-D mental model of an object that may be recognized and reasoned about more robustly than the initial unfamiliar view (Diwadkar and McNamara, 1997). This approach is akin to the strategy of occasionally looking backward on one's path, particularly at decisions points in a trail, so that one may recognize the route on the return trip.

A general strategy, when looking to reduce cognitive load, is to try to solve problems in a way that takes advantage of the observer's mental resources. For example, we noted above that flying a UAV into a location within the plane of a geological feature (e.g., a fault plane) can assist in visualizing some perspective problems. When within the plane, one may take advantage of the visual system's ability to integrate over 100+ ms time scales (Rock et al., 1987) to get a sense of whether there are aligned linear features consistent with a large-scale planar feature that extend beyond the field of view of the UAV. In this case, the geologist would need to combine pan and tilt strategies to track along the plane of interest (Fig. 6)[2] and see, for example, whether a fault observed at one location expresses itself elsewhere in the landscape. This approach is not unlike being able to see what is on the other side of a hedge when one moves rapidly past it by integrating the various bits and pieces of the scene into a coherent whole (Kellman and Shipley, 1992).

Avoiding Positional Failure—How to Not Get Lost

The propensity for UAV pilots to become lost during a flight is common and likely a result of accumulated errors (e.g., Fig. 7) associated with all of the cognitive issues discussed herein. In this section, we discuss strategies for avoiding these positional failures. For simplicity, we divide these strategies into two primary categories: (1) preventive strategies intended to reduce the likelihood of becoming lost; and (2) reparative strategies intended to reestablish the operator's sense of UAV orientation and position if the pilot has become lost.

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[2] Michele Cooke first articulated this strategy. When teaching students, she refers to this as "swooping"; here, we adapt the wordier "visual scan for large-scale planar features" to avoid confusion with flight paths that swoop.

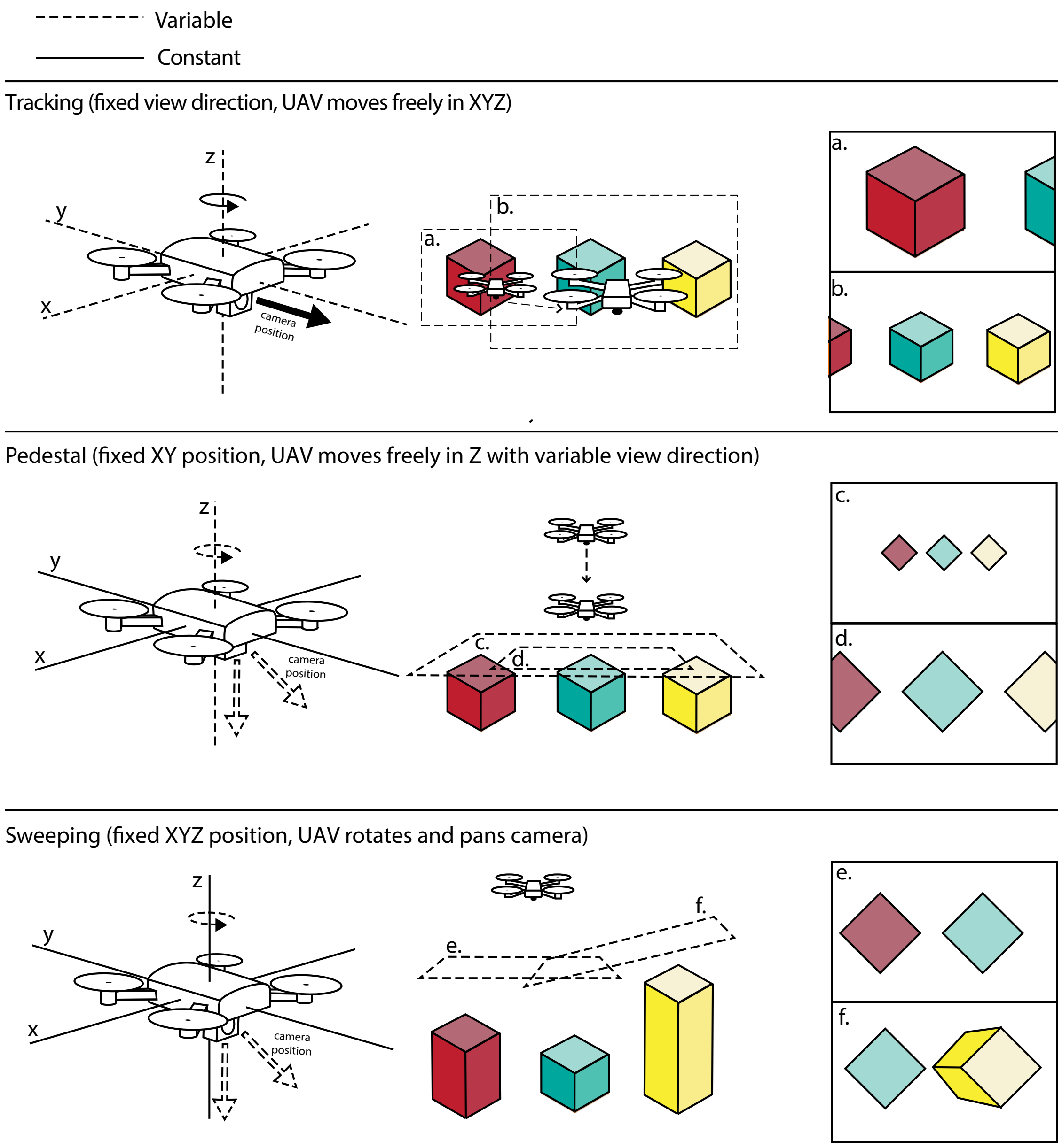

Figure 6. Schematic illustrations of unmanned aerial vehicle (UAV) strategies to mitigate difficulties associated with rapidly changing scale and view direction. UAV motion/orientation axes and camera pose schematics depict constant (solid line/arrow) or variable (dashed line/arrow) values depending on the strategy portrayed (e.g., the "tracking" shot employs fixed camera pose and view direction, while the UAV's *x*, *y*, and *z* positions are free to vary in space). Insets at right show the changes in the UAV's view of the rectangular prisms as UAV position or camera pose is varied.

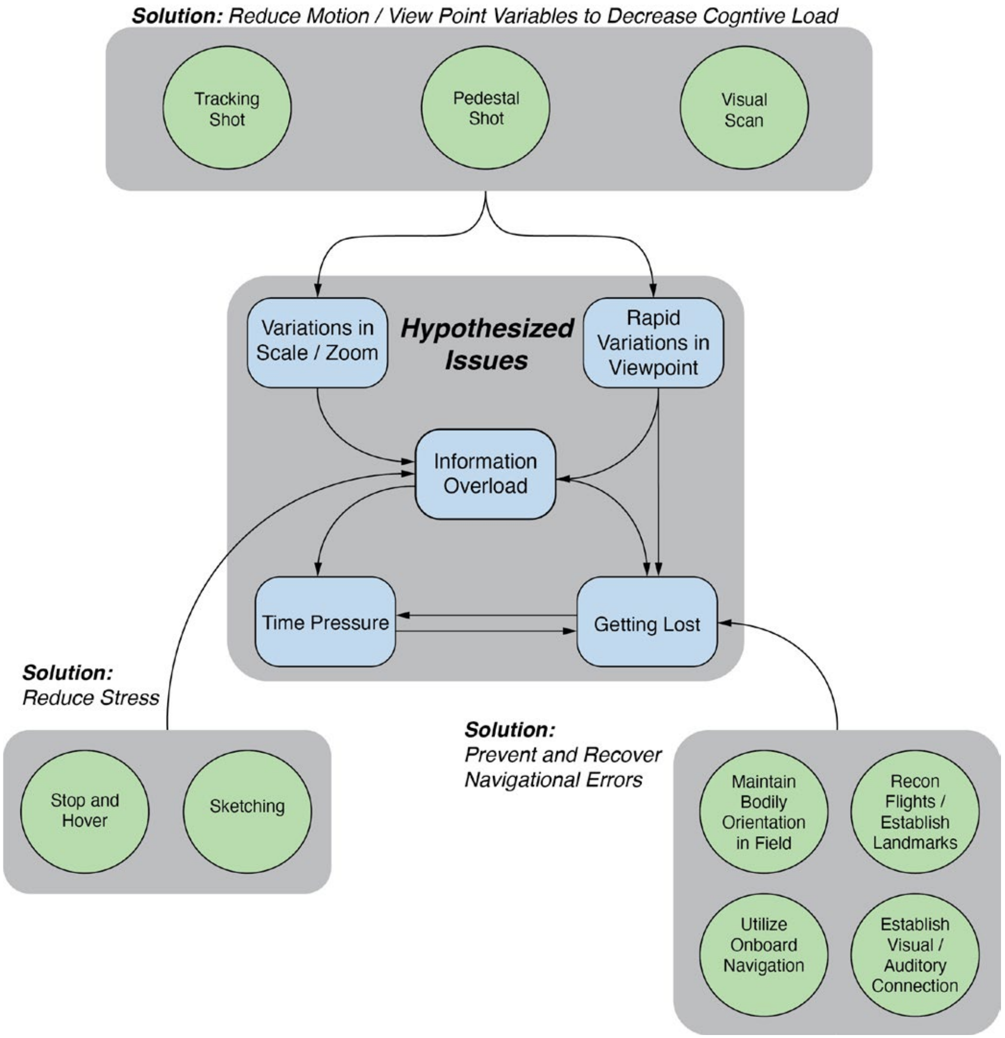

Figure 7. Diagram illustrating the hypothesized main issues inhibiting the in situ use of an unmanned aerial vehicle (UAV), the relationships among them, and proposed solutions that may lead to enhanced productivity when using UAVs in the field.

A relatively simple (but in our experience often neglected) strategy for preventing becoming lost in flight is to conduct one or more high-altitude reconnaissance flights purely for the purpose of orienting. One aim of these flights is to establish a sense of the cardinal directions in the field area by using distant landmarks (sun, sea, mountains, etc.) that are visible from anywhere in the field area. During these flights, the pilot/observer should refrain from making detailed observations or interpretations about the local geology, with the possible exception of establishing geological landmarks that may be useful for later navigation. Areas of potential interest for making additional observations may also be identified during these flights. Importantly, the UAV should be landed prior to beginning flights for the purpose of geological observation to allow time for the local landscape to be remembered and considered. This break could also be used to review video from the flight or make a quick sketch map, to further aid memory. This break also avoids time pressures associated with reduced battery capacity following reconnaissance.

Following the large-scale survey flight, if a particular area is going to be the focus of extended work and numerous UAV flights intended for observation and interpretation, we recommend that a reconnaissance flight should be conducted that focuses on the establishment of at least three distinct landmarks within the area of interest. These landmarks should be viewed from a variety of different perspectives, preferably in such a way that their positions relative to one another are readily visible.

Finally, an additional strategy for reducing the potential for navigational errors is to ensure that the UAV pilot maintains their personal orientation along a cardinal direction. That is, the UAV pilot should not attempt to turn their body in response to the UAV flight unless absolutely necessary. Our observation of experts during UAV use in the field indicated that this strategy is counterintuitive; most were inclined to move around and thus change their orientation in the field area while the UAV was in flight. This action almost invariably led to confusion regarding both UAV position and camera orientation, which was avoided when the pilot maintained a fixed (preferably cardinal) facing direction.

Strategies for reestablishing position after becoming lost may build, in part, on those strategies utilized for prevention. If a series of readily identified local landmarks is established prior to flight, for example, then these should be useful in re-stablishing one's position during moments of uncertainty. This strategy may be aided by gaining elevation such that a larger portion of the operating area is visible to the UAV's camera. Gaining elevation may also be useful in some circumstances that allow the UAV operator to reestablish visual contact with the initial launch location or vehicle (providing it is sufficiently close to resolve). Small but rapid translations in the UAV's position such as flying side to side may also be useful in providing auditory clues, in the form of rotor turbulence, to the UAV's position.

Perhaps more simply, we note that the majority of commercial UAV systems offer specific mechanisms for reestablishing position when lost. The DJI Mavik that we employed in our field tests, for example, has two mechanisms that offer substantial aid in moments of uncertainty. The first is that the control software and video feed on the iPad include a miniature map showing the UAV's view azimuth and motion direction. This miniature map also includes a two-dimensional flight path depiction and the location of the launch point, although the former can quickly become unintelligible if the flight path was complex prior to becoming lost. In many cases, the geologists found it useful to simply point the UAV back toward the launch point and fly it in that direction until visual contact was reestablished. When all else fails, the system also includes a "return to home" button, which, when activated, will instruct the UAV to automatically return to the launch point and land. Interestingly, our observation of experts using UAVs in the field suggests that the need to use these built-in tools is not entirely intuitive. Users seemed unaware of the accumulating error until it was obvious by way of a breakdown in what was expected and what was seen. New users may benefit from practice in a complex, but low-stakes, environment to appreciate the potential for getting lost and how to mitigate the risk. It is possible that the hesitancy to simply return the UAV to an overhead position and start over reflects habits formed during traditional field geology, because returning to a point of origin and starting over when lost: (1) rarely occurs, as the nature of being "lost" on foot is quite different, and (2) may require several hours (and in some remote areas, days) to complete.

Stress Reduction during UAV Use

The expert UAV users we observed in the field often reported some amount of stress during flights. This stress was most often described as being associated with information overload, being lost, or time pressure related to UAV battery life and associated limitations on flight time. Given this is, we suggest that all the previous strategies to mitigate these challenges will also aid in stress reduction.

We recommend two additional strategies for reducing stress during UAV operation. The first is simply to stop and allow the UAV to hover in place while the situation is assessed. A few minutes spent considering the landscape, objectives, and problems have a limited cost to the battery life of most modern UAVs but may offer substantial relief to the operator, thus increasing the "productivity" of the flight. Using our DJ Mavik system, for example, a 2 min rest period accounts for less than 10% of the battery life during a 20 min flight. A separate, but related strategy is to take time to sketch the landscape or a feature of interest while the UAV is hovering in place. As has been shown by a variety of previous research (Ainsworth et al., 2011; Gagnier et al., 2017; Gobert and Clement, 1999; Johnson and Reynolds, 2005), sketching supports spatial processing and reduces cognitive load, which should reduce in-flight stress. Finally, although requiring postflight work, the ability to review the flight video may also provide a reduction in the stress. Knowing one can watch a recording of the UAV flight and more deeply analyze the geology, evaluate working hypotheses, or negotiate meaning between two geologist's ideas may allow one to be less stressed while in flight.

■ CONCLUSION

The use of UAVs in field geology provides significant benefits to a geologist but comes with cognitive challenges. These challenges include processing variations in viewpoint and scale, information overload, disorientation, and stress related to time constraints. Currently, geologists appear to employ strategies similar to those they would without the UAV, such as climbing up to a high point and walking along or across strike where possible. The ability of the UAV goes beyond these effective strategies. We have presented a series of strategies that can help to support novice UAV pilots and geologists, including minimizing geological cognitive processing, avoiding getting lost, getting unlost, and minimizing stress levels.

As commercial UAVs are becoming increasingly affordable and used in field work, they should be useful for more than photogrammetry. Though Hansman and Ring (2019) provided a detailed workflow for post–field work analysis, here, we expanded on the in-the-field needs. We advocate incorporating UAVs into a geologist's field workflow to conduct analyses in real time. To support this new workflow, training programs for novice pilots could be developed to practice the techniques summarized here prior to traveling to field sites. Further research should also be conducted to understand how to develop proficiency in the human-computer interface required to pilot UAVs. We note that remote spatial exploration is not unique to in-field UAV usage, so research from diverse fields ranging from robotics to virtual navigation in games can advance best practices for training UAV pilots for in-field geology workflows. As new technologies for enhancing field practices become available, we broadly advocate for simultaneous development of the disciplinary tool and support for the mind using the tool.

APPENDIX: UAV TERMINOLOGY

As part of developing this report, we recognized the value of clearly communicating spatial information about the UAV position and how it was moving in space. We list the terms of art we adopted, borrowing many from camera directions for film making. We stress that all UAV users should refer to local, state, and/or federal requirements regarding UAV use and safety.

Vantage point—position of the UAV

View direction—orientation of the camera of the UAV

Pan—change in camera orientation in the horizontal plane

Tilt—change in camera orientation in the vertical plane

Pedestal shot—change in altitude of the UAV during which the camera maintains a horizontal position but moves vertically

Tracking shot—change in horizontal position of the UAV where the UAV flies in a straight line with the camera pointing to one side: the view direction is constant, but the vantage point changes

Zoom level—a combination of magnification and/or change in view distance

Visual scan for large-scale **planar features**—view direction changes but the vantage point remains fixed

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