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Review

Digital Weather Information in an Embodied World

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Abstract: We review the emergence of digital weather information, the history of human embodied knowing about weather, and two perspectives on cognition, one of which is symbolic (amodal, abstract, and arbitrary) and the other being embodied (embodied, extended, embedded, and enacted) to address the question: *Beyond the general weather information they provide, to what extent can digital devices be used in an embodied way to extend a person's pick-up of weather information?* This is an interesting question to examine because human weather information and knowledge has a long past in our evolutionary history. Our human ancestors had to pick-up immediate information from the environment (including the weather) to survive. Digital weather information and knowing has a comparatively short past and a promising future. After reviewing these relevant topics, we concluded that, with the possible exception of weather radar apps, nothing currently exists in the form of digital products than can extend the immediate sensory reach of people to alert them about just-about-to-occur weather—at least not in the embodied forms of information. We believe that people who are weather salient (i.e., have a strong psychological attunement to the weather) may be in the best position going forward to integrate digital weather knowing with that which is embodied.

Keywords: cognition; digital technology; embodied cognition; informatics; smartphones; weather

check for updates

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1. Introduction

Our globally connected society is increasingly utilizing digital devices (smartphones, tablets, and computers) to consume weather observations and forecasts along with climate outlooks and news about global climate disruption. Cell towers can geolocate our devices and then deliver weather information, including critical watches and warnings. We can live-stream the video of a severe weather outbreak and write about weather on social media.

Our capability to receive and send detailed weather information is unprecedented, but not without challenges. The sheer number and the variable quality of digital weather products and apps may provide conflicting information that can challenge users to understand the most important messages. Similarly, timely, accurate, and detailed weather warnings delivered to smartphones have not uniformly led to higher levels of compliance with warning messages or their recommendations for sheltering [1,2]. Sometimes a digital weather warning functions as an alert to an event so that people go outside to observe it—and stream it—rather than to take shelter [3,4].

This leads us to query the nature and capabilities of digital weather information as a comparatively recent contributor to weather information and knowledge alongside the embodied experience of weather. Embodied weather experiences have a long history as a fundamental way of weather-knowing over the course of human history [5]. The primary question we consider here is: *Beyond the general weather information they provide, to what extent can digital devices be used in an embodied way to extend a person's pick-up of weather information?*

Addressing this question is significant for several reasons, the first of which pertains to the burgeoning use of digital platforms to provide weather information to end users, along with the abilities to both assimilate and analyze large meteorological data sets and to understand societal responses to weather events from the big data perspectives afforded by social media [1,6,7]. Second, with the advance in the availability and accuracy of digital weather products, societal responses to severe and extreme weather events have not always followed suit [3,4]. Increasingly, it appears that peoples' responses to weather events represents a melding of digital forecast products with a person's local reading of weather conditions [8] Third, and relatedly, as the time for a forecasted weather event approaches (e.g., rain, windy conditions, cold) the words and graphical information from the forecast are reconciled or grounded in embodied experiences of the weather as it occurs. Here, descriptive words or graphical information about the future are given fuller meanings in the experienced present. Fourth, the consideration of digital and embodied perspectives on weather information will enable a better understanding of the functionality needed within digital products so that they can, in the future, extend the sensory and perceptual reaches of weather consumers [9]. Fifth, although embodied and symbolic/digital perspectives have been compared generally within cognitive and ecological psychology, no research has yet examined these perspectives in the context of weather [10–14].

Within this review article, we first discuss the historical evolution of digital weather information. Second, we examine the embodied perspective on weather, which has occupied a position of primacy in the way people pick-up information about their environment. In the third section we compare digital and embodied information of the weather and discuss the challenges of and limitations of each way of knowing. The interfaces of embodied and digital weather information are dynamic, and in some cases, potentially discrepant, which raises questions about the ways people may use sensed and digitally supplied weather information synergistically to guide their behaviors. We conclude with a discussion of the possible ways that embodied and digital/symbolic weather information could be used together. Here, we consider the roles of weather salience, which involves the ways people find weather to be psychologically significant [15,16]. Weather salience is a promising disposition for helping people to integrate embodied and digital experiences of the weather. Finally, we consider the types of weather information and features of digital products that may make information embodiable.

2. The Emergence of Digital Weather Information

2.1. The Internet and Smartphones

Due to computers, the internet, and the Internet of Things, we can digitally observe the weather with a level of precision and accuracy that was impossible even 20 years ago [17,18]. The history of these digital capabilities reveals that weather data, maps, and satellite images first became publicly available on the internet in 1993 through the University of Michigan and the University of Illinois [19]. Before this time, text-based weather information was available through the University of Michigan beginning in 1991 [19]. Interactive weather information from the National Weather Service (NWS) first became available online in 1995 [20]. While in the mid 1990′s it was possible to receive and retrieve weather information on cellular phones via text messages (e.g., the short messaging service, SMS), it was not until the advent of the smartphone in 1999 that internet and app capabilities for obtaining weather information became available [6,21].

A decade ago, only a small minority of weather consumers in the United States obtained their weather information from government or private sources on the Internet or through smartphones [22]. At that time, the primary sources for weather were local or national television stations. Smartphone use, however, has burgeoned since 2009 to become the dominant modality through which people obtain weather information [23–25]. A recent study documented that approximately 95% of a sample of undergraduate millennial students obtained their weather information from a smartphone [7].

Along with these trends in smartphone use, weather-related smartphone apps have also proliferated. We counted 5993 weather apps for the Apple Iphone as we prepared this article. This represents a nearly six-fold increase in the 1000 apps for weather that existed in 2009 [23]. An important caveat, however, is that apps may erroneously suggest a greater degree of precision of weather observations or forecasts over an area or over time than is possible given the current capabilities (i.e., observation network density and forecast model precision) that exist within atmospheric science [24,26]. The high-tech appearance of many weather apps can also imply a greater degree of certainty (or lack of uncertainty) than is warranted [25,27].

2.2. Social Media

Social media platforms, most notably Facebook and Twitter, have become forums for disseminating weather information and responding to the aftermath of severe weather events. Auxier and Anderson noted that, as of 2021, approximately 69% of adults in the US indicated that they have used Facebook at least once (a statistic which has remained nearly-unchanged since 2016) while at least 23% of US adults have used Twitter [28]. Social media allows participants to post their weather-related experiences to Facebook or Twitter. At times, such citizen-based science on social media can be helpful [29]. At other times, the information that people post or forward on social media may be inaccurate, unreliable, or simply fake [30–32]. Thus, the National Weather Service maintains a presence on Facebook and many forecast offices not only monitor various Twitter hashtags but create their own to vet and curate reports of significant weather events [33]. The real strengths and benefits of social media information seem to accrue in the aftermath of severe or extreme weather events when it is used to coordinate damage reports, communicate needs, and to assist in recovery efforts [29,34].

More recently, virtual, augmented, and immersive reality technologies have begun to arrive on the weather scene to more cohesively merge digital and embodied experiences of weather in day-to-day broadcast television, hazard communication, and educational contexts [35–39]. While integration into wider consumer behavior may be some time off [40–42] due to scalability and integration with current devices and accessibility standards, these technologies will usher in new ways of weather-knowing with an integration of the digital as well as the physical.

2.3. Limitations of Digital Media

Regardless of the specific electronic platform that people may use, the digital experience of weather is two-dimensional and thus indirect because it is delivered to a screen (i.e., on a desktop monitor, tablet, or smartphone screen) and involves immediate access to numbers, maps, or video with keystrokes or swipes. In addition to maps or text information, weather videos may provide sounds of weather events and include some narration, so at most there would be images on a screen and sound from a speaker. While sight and sounds may be among the most important of the human senses given their role in adaptation [43], digital platforms currently do not provide as much to convey a sense touch, smell, and taste. Words, images and sounds from digital devices do most of the work in communicating or suggesting the nature of other sensory qualities [40]. Moreover, there is a difference between the experience of a digital representation of the weather as images and sounds and the embodied visual and auditory perception of that weather as it occurs around someone [10–12].

2.4. Grounding Symbols That Are Abstract, Amodal, and Arbitrary

These observations raise the issue of symbol-grounding of the words, phrases, or map images that appear in digital weather products. To what extent are linguistic symbols or map-based images related specifically and concretely to a physical object or condition, especially to one that a person may perceive [13,14,44]? Going outside to see a weather event (e.g., lightning, hail, and a tornado) after receiving notice of it digitally is an example of symbol-grounding (although one that can be dangerous). This leads to defining three terms central to the symbolic approach. Linguistic symbols, including those in digital weather products, are *3A* (*abstract*, *amodal*, and *arbitrary* in their relations). Words or numbers in a digital product are abstract because they can refer to many things (i.e., average conditions over a wide area), to at least a single occurrence of something within an area such as rain, or relations or quantities that are unrelated to the physical weather conditions. Again, notification of *a tornado* may prompt a visual search from a window or outside for *the tornado* that may affect a person. Such words and numbers are also a modal because they represent meaning irrespective of the sensory modality (e.g., hearing and vision) that perceives them. Finally, words and numbers function arbitrarily because there is no fixed relation between them and what they represent. For example, although they can be used to qualify or quantify the weather conditions of a place, as social constructs the weather terms *blustery*, *cold*, *severe*, or 29.86 have no pre-determined meanings in the atmospheric environment. In the context of weather forecasts, words, numbers, and images have a stochastic rather than deterministic relationship with the physical conditions that they intend to represent [45]. Overall, digital devices bring a wealth of linguistic and symbolic weather information to a person, regardless of their location. However, to what extent can this information supplement or combine with that which people perceive around them in real time?

3. Embodied Weather Information

Embodied experiences of weather are those that people have when they are outdoors, within the direct influence of Earth's atmosphere, so that they can sense and observe the weather directly. This is a primary, direct and embodied experience of the *atmosphere* that is not mediated by technology [10,11,45–47]. The ecological psychologist and philosopher Edward Reed [46] (pp. 2–3) maintained that:

For [F] or understanding our place in the world, ecological information is thus primary, with processed information secondary. It is this relation between primary and processed experience, in which the balance should be tilted toward primary experience, which has been disrupted and degraded by modern life. It is on the firsthand experience—direct contact with things, places, events, and people—that all our knowledge and feeling ultimately rest. There are differences—and real limitations—to indirect experience, to being told about things as opposed to observing them for oneself.

Embodied experiences of weather rely upon using multiple senses in uncertain environments and then integrating the information into perceptions [13,14,43,46,47]. This process allows the person or animal to determine the event(s) that were most likely in producing what was detected in the environment so that behavior can be adjusted accordingly [47,48]. The use of multisensory perception for survival involves the emotional system, especially when an event may be hazardous [49–53]. While vision is a primary modality [54], sounds and smells also provide adaptive information that may give rise to emotional experiences (e.g., of alarm, fear, and anger). Smell may elicit emotions and cue memories of past experiences (e.g., the smell of a spring rain amid blooming flowers cues memories of past spring times [53,55]. Similarly, changes in the loudness and pitch of natural sounds like rainfall induce changes in human emotions [56,57].

The embodied experience of weather involves what ecological and cognitive psychologists refer to as *4E* (i.e., *embodied*, *extended*, *embedded*, and *enacted*). Embodiment involves the influence of weather on the body and its effects upon cognitive, affective, and behavioral processes. Relatedly, especially while outdoors within the weather, people are *embedded* in the prevailing weather of the time and this immersion can similarly affect the body and mind. As goal-directed and survival minded beings, people *enact* their behaviors in the context of the weather and climate affordances that exist [43]. Ecological psychologists also include the *extended mind* as one of the 4E because, as embedded and embodied beings who attempt to perform behaviors, we can find ways to offload cognitive processes to our environment [10,11,58–61]. Signs and indicators within the environment may provide reliable information about the present or impending weather that make it unnecessary for people to engage in deeper thinking or problem-solving.

Several examples illustrate the embodied approach in using perceptions of present weather (also known as information pick-up) to guide actions. First, a person may open a door and see that snow or freezing rain has accumulated on the walkway outside. As the person puts a foot onto the walkway and notices a slippery surface, he or she may hold more tightly to the railing, take smaller steps, look for spots on the walk that are not icy, and so forth. Second, approaching dark clouds, winds that blow from the direction of the clouds, and the smell of rain may together foretell an immediate downpour. The person in this situation may then seek safe shelter from the approaching shower or thunderstorm. Third, a person may have just driven to the market only to find that a heavy shower is occurring. The sights and sounds of the rain indicate an ebb-and-flow pattern. Sometimes the rain stops briefly as the sky begins to lighten. While the person's smartphone weather radar app shows a solid area of rain overhead (at least perhaps until the app updates again in a few minutes), the person notices that the rain tapered off. Taking this into account along with the distance from the car to the market's covered walkway, the person decides to make a run for it. In each of these examples, the person is using multiple sensory systems to perceive immediate weather conditions and to act accordingly. Such a manner of perceiving at the precipice of making goal-directed actions or behaviors is known to ecological psychologists as perception-action [43,58–61]. The person has confidence in his or her weather perceptions and this immediately informs actions within that weather.

Our human ancestors exemplified the *4E* approach in relying upon their senses to discern the weather and to foretell its tendencies [5]. Within some cultures people use a close reading of the skies and seasonal (phenological) changes in flora and fauna to determine the timing of planting and harvesting. Similarly, phenological information and accumulated experiences of past weather helped to predict wet or dry periods [62–64]. With the onset of global climate disruption, however, meteorologists and government officials have begun to assist people in some of these cultures, for example, in Burkina Faso to incorporate seasonal forecasts into agricultural planning and practices [64]. People thus exhibited confidence not only in their embodied weather observations but also exhibited confidence in the value of this information for present behavior of future planning. That people were attuned to the conditions of their locale and engaged in an embodied uptake of weather information lends a sense of poignancy to their weather experiences. Here, weather-knowing is first-person, involved, and encompasses procedural knowledge.

A rich heritage of weather wisdom steeped in direct observation and sensing emerged within North America in the era leading up to the 20th century [65,66]. Typically, this wisdom was developed for a place and described as a sequence of occurrences. Sometimes weather relations were phrased in conditional statements, such as this observation offered by Luke Howard: "If cirrus clouds form in fine weather with a falling barometer, it is almost sure to rain." [66] (p. 12). Similarly, people evaluated the airs and waters of places, along with prevailing winds and seasonal changes, to find the most desirable places to build a home [67]. Some people considered the development of a *sense of the weather* and what the weather brings as an important life skill for people up to the mid-20th century ([65–69]). The psychologist Hall, G.S. discussed the content of children's knowledge about weather and their use of it for practical purposes [70]. Now, educators have a renewed interested in embodied experiences of weather because this may build openness and motivation for sustainability in the face of global climate change [71,72]. In addition, people who work or recreate in remote regions rely upon a reading of winds, clouds, pressure, and other indicators to foretell the weather from present conditions [66,73,74].

4. Comparisons of Embodied and Digital Weather Information

Beyond the descriptions above, a fuller comparison of embodied and digital weather information is warranted to understand the strengths and limitations of each way of knowing, and perhaps more importantly, to understand the challenges that people may experience in interfacing embodied and symbolic/digital information in real-time. Our goals in making these comparisons are to increase the usefulness of weather forecasts and to help people to be more mindful of their embodied weather experiences. Table 1 summarizes the differences and similarities of each way of knowing for several points of comparison. In addition to these comparisons, we also discuss embodied and symbolic weather knowledge according to: 1. Their primacy and recency over the course of human history; 2. the issues involved in upscaling information from the point perspective of a person versus the downscaling of symbolic weather information for a wide area to the point a person occupies; 3. the tension involved between the need for specific, perceptual-actional weather information versus representation of the present or future weather in a more general weather forecast; 4. issues of uncertainty and confidence in each way of knowing about the weather; and 5. the relationships of time with symbolic and embodied perspectives on the weather.

Table 1. Comparison of embodied and symbolic (digital) weather knowledge.

Point of Comparison	Embodied Weather	Symbolic/Digital Weather
Relationship to the person	*4E* (embodied, extended, embedded, enacted)	*3A* (abstract, amodal, arbitrary)
Direction of information acquisition	From point location to area, bottom-up, *inductive*	From area to point, top-down, *deductive*
Relationship of sensation to information pick-up	Grounded in physical sensation	Not grounded in physical sensation
Availability of information	Information *available* for immediate pick-up	Information may be *present* but not immediately *available* and may need transforming or down-scaling to become *available.*
Relationship with time	Present-time and immediate future	Present-time, immediate future and beyond.
Type of information	Procedural (*knowing how*) that may contribute to semantic knowledge	Semantic (*knowing that*)
Uncertainty: Perception and action in present weather	Deterministic to pseudo-deterministic	Pseudo-deterministic to stochastic
Uncertainty: Expectations for future weather conditions	Pseudo-deterministic to stochastic	Pseudo-deterministic to stochastic

4.1. Primacy-Recency

Embodied ways of picking up weather information and building weather knowledge have accompanied human evolution [5,75,76]. Being able to pick-up information from the routine weather of the season or to respond to threatening weather such as a flood contributes to human survival. Thus, both with respect to time and significance for survival, the 4E ways of knowing about the weather occupy a position of primacy. Embodied ways of knowing are grounded in physical sensation and information from the atmospheric environment is available for immediate pick-up (see Table 1). Given the attunement of our sensory modalities to the natural environment, embodied weather information always will be available, and in fact, may be difficult to ignore [76,77].

The emergence of synoptic meteorology [17] has been followed much more recently, as described above, by the delivery of digital weather information. This newer information offers fresh opportunities to go beyond embodied perceptions that a person can develop at and within a specific point and time. A small, but significant caveat is that although the information may be *available* on one's smartphone, this does not mean that it is *present* (as is true for embodied perceptions) to the person (i.e., the app must be accessed and the information understood, adapted, or translated to a person's individual goals or behaviors at the time, see Table 1). Regardless, the recency of technology, and the expectation that it will continue to grow in its capabilities—far more quickly than the pace of human evolution—might suggest that embodied weather information and knowledge would become obsolete in the future. At least, the present trends imply a greater reliance on all-things-technological, including the digital / symbolic 3A weather products [27,78]. As we discuss below, however, a progressive abandonment of 4E information and knowledge about the weather—even if this were possible—may be premature for several reasons.

4.2. Upscaling and Downscaling: Model Resolution and the Probability of Precipitation (PoP)

Another set of challenges in the complementary uses of embodied and digital weather information concerns the directionality of knowledge and issues of geographical and temporal scale (see Table 1). Embodied weather information and knowledge is inductive in nature given that what a person senses and perceives at his or her location could be scaled-up to a wide area or extrapolated from the present time to the near future. As a *perceiver-at-a-point*, the person's accumulation of information and building of knowledge is from the bottom-up, as illustrated in the example above of waiting for a shower to subside, or the African farmer who uses seasonal phenological signs to schedule planting [10,15,16,64]. In contrast, digital and symbolic weather information is assimilated from large areas (e.g., continents, regions, states, and counties), analyzed synoptically, modeled, and then summaries of present weather or forecasts for future conditions are made [17]. This is a top-down process in which the information and forecasts for a person at a location must be down-scaled both with respect to the geographic area and to time.

The concern here is that discrepancies can exist between the embodied experience of weather information and knowledge and that which is available through digital platforms. There are at least two reasons for this, with the first concerning the immediacy of present weather observations. Currently, weather radar and satellite technology can provide near-real-time coverage for given regions and display the information on a smartphone or tablet-based device, as well as personal computers and even some IoT appliances. Other observational data (e.g., surface weather maps showcasing temperature, wind, and humidity readings; atmospheric soundings; heat and UV indices; rainfall amounts) are only updated periodically. The NWS makes much of this information available every hour, with weather radar updating approximately every 10 min [79]. On other sites such as Weather Underground, the updates may occur every few minutes or seconds [80]. Unlike weather radar and satellite information, data on other meteorological variables is usually only available at the locations of ground-based observing stations. Thus, the proximity of a person to one these stations may determine the extent to which the NWS readings are consistent with or discrepant from what a person can sense or observe.

This often leads people to erroneously think weather forecasts are "busted", whether it, for example, is raining and the forecast called for sunshine or it is sunny and the forecast was for rain. This demonstrates a failing of digital weather apps and hyper-specific, point-based, digital weather information: People do not typically know that when the NWS provides a city-based forecast, and even sometimes point-based current-condition information from their National Digital Forecast Database system [81], it is based upon the location of the station which houses their official observing equipment and not the person's actual location.

The second reason concerns the spatial resolution of current forecast models. The global model from the European Center for Medium Range Weather Forecasts (ECMWF, [82]) is nine square kilometers, meaning that the weather conditions are assumed to be homogeneous within gridded boxes (9 km on a side) that cover the Earth. The United States' Global Forecast System model (GFS, [83]) has a coarser resolution of 28 km per side. The highest resolution model that exists at this time, updated hourly, is the High-Resolution Rapid Refresh model (HRRR, [84]) with model grid boxes that are 3 km on each side. While forecasters may use a blend or ensemble of models to prepare an outlook, the issue remains that the conditions are expected to be the same over areas that are large with respect to the scale of people and their abilities to perceive the weather of their locations. For example, assuming a suburban population density of 730 people per square kilometer, on average, in the US [85], almost 60,000 people (or embodied weather perceivers) would be forecasted to have the *same* weather conditions within one of the grids of the ECMWF model.

A problem that comes from this top-down approach concerns the well-known probability of precipitation (PoP). The PoP is a number (ranging from 0% to 100%) that conveys the likelihood of at least 0.01″ of precipitation (rain, snow, etc.) occurring within a given area over a certain time period [86]. Many people are familiar with, and the meteorological literature contains, accounts where a forecast of 70% probability of precipitation results in *most* of a forecast area not receiving any rain or snow [87,88]. As at least 0.01″ of precipitation occurred *somewhere* in that region, however, the forecast is verified (i.e., considered accurate meteorologically) [88]. Summer afternoon thunderstorms are especially challenging to forecast with some areas getting a good rain while others remain dry—all within the area of the same PoP [89]. The issue is as follows: Top-down forecasts permit stochastic statements to be made about events *within an area* however these may not accord with embodied experiences of individuals at *points within that area*. Top-down forecasts, although statistically useful and continuously improving, are not necessarily human-scaled and regularly may differ from the weather information that is available for people to perceive with a high degree of confidence at their locations [87,90].

4.3. Weather as Background (3A)—Weather as Foreground (4E)

A third dimension of comparison relates to the focus of peoples' weather information needs given what they are *doing*. The 3A digital/symbolic is intended to represent current weather conditions and to convey weather forecasts so that people can *accommodate* planned activities or projects *around* the weather [91]. The process of accommodating the forecast may involve attempting to understand or problem-solve what forecasts may mean or imply for a planned activity (i.e., "what does a heat index of 90 and calm wind *mean* for how long I should run outside?") [92,93]. In the 3A stance, weather and symbolic weather products function as a background onto which human activities are foregrounded; peoples' behavioral spaces are encompassed in a larger weather information-space. While it is true that we exist within and under the weather, digital products describing the weather cannot lay claim to this position of primacy.

The 4E position is that people are not so much trying to cognitively represent or predict the weather as they are trying to accomplish specific actions (e.g., fulfill daily life tasks of school or work, recreation, or travel) given the weather's behavior [91–93]. Here, plans and behaviors are the background onto which the weather is superimposed (foregrounded). Similarly, from the embodied position, people assimilate the weather to their activities (e.g., "I want to go running, how do the conditions *feel*?" From the 4E position, weather is an affordance for specific behaviors–not something that is general or abstract, from which behavioral plans are deduced [43,47]. Weather occurs as a series of events within the activity life-space of the person; it is *perceived* and accordingly acted around or accommodated in whatever context it appears, just as the body-mind perceptual system receives sensory input from the world and interprets it behaviorally and cognitively [94].

4.4. Uncertainty

Finding ways to communicate uncertainty in different weather products has been a priority of the weather enterprise for over a decade [95–99]. The 3A and 4E approaches involve different kinds of uncertainty depending on present or future timeframes. The 3A information possesses pseudo-deterministic to stochastic uncertainty for both present weather conditions and forecasted future conditions. While present weather variables can be measured with a high degree of precision, these conditions are for the single-point location of the observing site. Such present weather readings may be *representative* or *indicative* of meteorological variables as one progresses further away from the observing site. At some locations near the observing site, however, such as an exposed hilltop or a shady valley, the weather may vary considerably from weather station readings–hence a pseudo-deterministic level of uncertainty (see Table 1). The values of weather variables can be determined, but over wide areas with a sparse reporting network, the information takes on a progressively stochastic or probabilistic character. Pseudo-deterministic to stochastic uncertainty also exemplifies the 3A forecast. Short-term forecasts or *nowcasts* possess a higher degree of confidence. However, for longer timeframes and wider areas of weather coverage, 3A forecasts possess a larger stochastic component (e.g., tomorrow's probability of precipitation).

People who obtain present weather information from smart devices should remember that once their device is geolocated, an app will supply weather information that is taken from the nearest NWS observing site. While hardware and apps are available to turn a smartphone into a mini observing station [100,101], most people do not obtain their weather information that way. Similarly, maps and other graphics may be zoomable to the location of the smart device, but apps often fill-in (interpolate) and smooth data. For example, composite radar images, which displays the average of radar scans across the volumetric column in the atmosphere, is typically shown to the detriment of the user who thinks that it is an accurate representation of current rainfall coverage as would be seen via base reflectivity imagery [102]. Such imagery and graphical displays may imply a greater degree of certainty and precision in weather variables than is possible or actually shown.

Another consideration bearing upon the uncertainties of 3A weather information concerns inconsistencies between the information (i.e., present weather or forecasts) that exist between different weather apps [24]. Sometimes such apps produce discrepancies: due to 1. delays or lags in updating information, 2. using different approaches or algorithms for processing data from the NWS, and/or 3. using proprietary data sources the create a *new* product altogether. Several researchers have observed that such product inconsistencies undermine users' trust of weather information products and increase the uncertainty people experience [1–3,26,30–32,103].

Uncertainty about weather from the embodied perspective differs from the 3A approach. For present weather, uncertainty involves the person's confidence in his or her embodied experiences. That is, a person will tend to exhibit confidence about what is felt, seen, heard, or smelled weather-wise, given present goals and plans; the example above about waiting for rain to subside illustrates this. The uncertainty in this situation may be deterministic or pseudo deterministic (see Table 1). For the 4E approach, uncertainty is not about producing a veridical perceptual account that accords with measured weather variables. Instead, uncertainly involves confidence in weather experiences given what the person is trying to accomplish; here again, weather information in this context comes as an affordance.

Forecasts made from the embodied standpoint are, like the 3A perspective, pseudo-deterministic to stochastic. This applies for anticipating the short-term changes in the weather (minutes to hours), through progressively longer timeframes. Like the 3A perspective, there are potential problems that come in over-reliance on the kinds of observed atmospheric or phenological indicators, as detailed above [Section 3]. While an embodied forecaster may have confidence in the signs and indictors of future conditions, these sources may ultimately prove to be no longer accurate, unreliable, or just wrong, especially with the changes brought by global climate change [8,62–64,104].

4.5. Time in Embodied and Symbolic Perspectives on the Weather

The concept of time occupies an interesting role in the weather in than in some languages such as French (*temps*), Spanish (*el tiempo*), and Italian (*tempo*), weather and time are conveyed by the same word. We take this to mean that to some extent as an unfolding series of events, weather is time-binding [105]. That is, the conditions that are forecasted or anticipated for the future merge in time with the present—and the present-embodied weather. Similarly, embodied weather continues to occur such that what was present-weather recedes into the past. Beyond these semantic and etymological relationships of weather and time, attending to both the weather forecasted for the future (over varying timeframes) and to the present, embodied weather can increase the understanding of what is valuable in both symbolic and embodied weather information; the informational utility of each approach can be maximized. Weather salience, to some extent, is a measure of a person's attention to the present and to the future of weather [15,16].

People can employ embodied and symbolic perspectives over comparable timeframes and can benefit from knowing the informational strengths of each one. For example, in the 12 to 24-h timeframe, symbolic forecasts from weather services provide an indication of expected conditions. Similarly, it is possible also to use current, immediate weather information at a point (clouds, winds, temperature, and pressure trends) to make a similar forecast [66,73,74]. Interestingly, there is some evidence that peoples' interpretations of cloud and rain (symbolic) forecasts are affected by the conditions they observe when the forecast is issued [106]. Similarly, both symbolic and embodied weather information are useful for immediate or short-fused events like thunderstorms, tornadoes, or floods. Many smartphone apps exist for receiving near-real-time updates on the tracks of thunderstorms or tornadoes [1,2,7,23,24]. While these apps may indicate that a person is within a warning "box" or region, embodied weather perceivers may see that the storm is moving away from them or that other immediate weather dangers have passed [24,25]. Similarly, the example cited above about a radar app showing rainfall while a person notices that the rain has subsided or stopped momentarily shows the relationships between symbolic and embodied perspectives and how a disconnect can exist between these. Appreciating such disconnects or observing consistencies can build engagement with both symbolic forecast products and present embodied weather so that knowledge and adaptability are enhanced [15,16]. In addition, such comparisons can indicate how forecast products and digital technology can be improved in time to provide a more seamless experience between the symbolic and embodied modes of weather experiences.

5. Towards an Integrative Stance

We return to the question we posed at the beginning of this article: Beyond the general weather information they provide, to what extent can digital devices be used in an embodied way to extend a person's pick-up of weather information? Is it possible to have the best of both the 3A and 4E information worlds? What might this look like now and going forward in time? Although 4E approaches to cognition have proliferated over the last 25 years and have demonstrated utility and potential over the more traditional 3A perspective, both approaches possess value [15–17,107–109]. While we have similarly emphasized the differences and contrasts between embodied and symbolic/digital information, each approach–as a tool for understanding cognition–has its optimal ranges of applicability. In addition to bringing digital weather products, the internet and smart devices have increased the pace of life–people are more mobile and more active than ever before. This also means that they are more likely to encounter challenges and the needs for psychological as well as behavioral adjustment that the weather poses [15,110]. The active-dynamic stance of embodied cognition fits well with mobile, active lifestyles. Nonetheless, the 3A approach functions well for describing weather (the *what* of weather), for developing prospective strategies (e.g., emergency management, agriculture, marketing) within timeframes that allow for deliberation, discourse, and deeper meaning-making to occur. In this regard, the embodied-symbolic relationship parallels the distinction that Wittgenstein [111] made between meanings developed quickly (in a flash) and those meanings that are more extended in time. Both are necessary in weather-life. Below, we discuss a psychological trait that is especially suited for bringing together embodied and symbolic experiences of weather. Finally, we discuss some features of 3A digital weather information that could maximize its usefulness to people.

5.1. Weather Salience

Weather salience is a human characteristic that involves the degree of psychological significance that the weather has for a person—how much the weather is part of a person's life such that they relate to it on multiple levels: 1. Sensing and observing the weather directly, 2. gathering weather information from multiple sources (like smartphones and the internet), 3. being impacted emotionally by weather and weather changes, 4. being attached to the weather of one's locale, 5. noticing the effects of weather on daily life, 6. noticing how weather events can result in disruptions or holidays, and 7. needing to experience variety and change in the weather [15,16]. People who exhibit higher levels of weather salience are interested in weather and are attentive both to the weather that they experience and information about the weather (i.e., from digital sources). Thus, weather salient people are likely to be in a good position to interweave both embodied weather experiences with what is available digitally and symbolically. Further, as a personality trait that is stable in time, weather salience may underlie the attunement to weather over varying time frames (forecasted future conditions and present conditions) [15].

Scores on the weather salience questionnaire (WxSQ) have correlated positively with perceptual curiosity and the ability to attend to weather-related stimuli in the environment [15,112]; consulting multiple electronic sources for weather information [12]; detail-orientation and pattern recognition [113–116]; trait openness, weather-warning awareness, storm preparation self-efficacy beliefs, and both generalized epistemic curiosity as well as epistemic weather curiosity [116]. Weather salient people thus bring an interest and acuity to the weather and to weather-related information products. Not surprisingly, weather salience is associated with perceiving greater value in and better understanding of the NWS weather products [16,117].

Possessing higher levels of weather salience has at least two implications for the integrative use of embodied and symbolic/digital information. First, although we have not quantified the relationship with respect to the WxSQ measure, weather salient individuals tend to be involved in citizen-science weather projects. This includes activities like storm spotting and chasing [118,119]; measuring and reporting daily rainfall through the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS; http://www.cocorahs.org, accessed on 9 June 2022) [120]; and observing, reporting, and recording weather on Weather Underground and other citizen-science websites [71,121].

Second, we have observed and Shermak and Whipple have gathered preliminary data suggesting that weather salient people are likely "the *weather people*" in their family and social networks [122,123]. This may mean that they are the ones who are viewed as the in-group weather *expert* who can explain a weather event or who can render an opinion in instances where digital apps convey ambiguous or conflicting information. Similarly, weather salient people may be able to interpret present, embodied weather experiences and how these are consistent with or discrepant from the conditions that are reported elsewhere or forecasted for the future.

5.2. Features of Embodiable Weather Information Needed in Digital Products

How can people make greater and more frequent use of digital weather information? One approach is through marketing and education about the features of different weather products and apps, especially to users who may possess specific needs such as knowing current UV levels or rainfall amounts for the planning of daily agricultural activities. Making users more aware of such products and encouraging their use does not alter the fact that information still exists in 3A forms. While these products and apps may provide weather information that is *useful* (or usable) for *something*, it is not necessarily formatted in a way that makes it of more utility, from an embodied perspective, unless or until a user has a specific need for the *something* that the app provides.

An alternative approach is more promising from an embodied perspective, but also presents greater challenges. Here, digital products and apps that allow users to cognitively offload information gathering and/or decision-making in real-time during life activities holds the most promise of leveraging the 4E features of embodied cognition. Such offloading can occur in two ways, the first of which involves prospective memory while the second way involves perception-action [124]. Of the two, using digital devices for prospective memory purposes is an *embodied-lite* and more passive approach that are familiar to people. That is, users can configure an app to provide information such as: 1. Alerts when the

UV Index, the temperature, or humidity reaches a certain level, 2. warning of impending precipitation, and 3. the occurrence of lightning nearby, and so forth. Additionally, a smartphone or tablet can be used to record the sounds and images (still or video) of current weather. In each of these uses, the digital device functions primarily as a memory of either experienced information or of instructions to alert the user when an event occurs. Users are not so much extending the sensory capabilities of their bodies or their thinking with the device as much as they are simply using it as a reminder or memory aid. One possible limitation, of course, is that the alerted information may be imprecise as it is obtained from sensors that may not necessarily be near to the user (Section 4.2). This first use of digital devices is the current *state-of-the-art* in digital weather information products. The challenge lies in taking digital weather information to the next, second level.

The second level of embodied cognition and offloading to digital devices has two requirements that should, by now, be familiar [9,125,126]. That is, the device or product should provide information to the perceiver-actor from the environment in a way that extends the sensory capabilities of the body for the spatial and temporal scale it inhabits. This requires that the weather information is body- and action-scaled for the person's environment given their goals and actions [59,60,125,126]. Operationally, this means that real-time, actionable weather information that is modality-specific and behaviorally-concrete holds the most promise of being psychologically incorporated and fully used in ways that 3A apps are not.

A close, but non-weather example exists in the GPS and smartphone apps that provide real-time driving directions, considering the location of the vehicle, the destination, and the sequences of turns and maneuvers necessary for navigating to the destination. These apps allow the driver to cognitively offload wayfinding (i.e., no need for using paper or digital maps, looking for street names, etc.) during the drive. Instead, as a turn or lane-change is needed, the just-in-time information appears in display or via an audible instruction.

Could real-time road-weather conditions be added to navigation apps? Currently, no integrated internet or smartphone apps exist that provides detailed, point-specific alerts about icy, wet, flooded, or foggy roads ahead (e.g., "ice on the road in one kilometer, slow down."), although recently, mapping technologies have begun to route users around weather warnings [127]. Near real-time information about precipitation and lightning does exist in weather radar apps such as RadarScope, MyRadar, and WeatherBug [128–130]. These apps provide alerts about the onset of precipitation (from radar) and integrate lightning discharge data to provide alerts about thunderstorms. One example of a crowdsensing highway weather app exists in Waze [131]. The Virginia Department of Transportation has worked with the app developer to provide fuller coverage for roads in that state [132]. These exemplify the first level of *embodied-lite* products. As users must access and manipulate these applications, however, they are not fully automated (as in the case of a display or an audible set of driving instructions). Nonetheless, the future potential exists, at least in the United States, for better spatial and temporal resolution of weather along major highways so that weather information during driving could be offloaded cognitively to an app. As the technology for disseminating near-real-time weather information (observations and forecasts) advances, additional research will be needed to examine the value of these products to digital consumers.

6. Conclusions

We began this article by posing the question: Beyond the general weather information they provide, to what extent can digital devices be used in an embodied way to extend a person's pick-up of weather information? After reviewing the emergence and progress of digital weather products and the concepts of both embodied (4E) and symbolic (3A) cognition, our best answer to the question is: In some limited cases, such as the onset of rainfall, it is possible to extend our sensory reach of the just-about-to-happen weather via smartphones. Beyond this, temporal and spatial resolution limitations in weather observation and forecasting capabilities preclude providing just-in-time weather information that people could use in real time to guide their immediate behaviors. Of course, this does not mean that digital observations and forecasts are of limited value—the weather enterprise is performing now better than it ever has [17]. Observations and forecast products can be used to guide planning and decision-making, but in a manner that is offline and less immediately informative compared to a person's own ecological perceptions [39,43]. To some extent, the current state of digital and embodied knowing may explain in part the finding that some people do not take shelter or make preparations for severe weather when alerted by a smartphone [2–4]. The displayed warning message and map is apparent, yet people may not perceive real consequences given what they are doing at the time. Further work at the nexus of just-in-time weather warnings may help to achieve better compliance with digital weather information. In this regard, weather salient individuals bring attunement both to the weather's immediate behavior to information offerings they receive about the weather from other sources. Going forward, weather salient people may be early adopters or innovators who can show others the way to use embodied and digital information together [133].

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